SUBSURFACE STRATIGRAPHY OF THE MIDDLE AND UPPER DEVONIAN CLASTIC SEQUENCE IN SOUTHERN WEST VIRGINIA AND ITS RELATION TO GAS PRODUCTION

by

Donald W. Neal

Submitted by the

West Virginia Geological and Economic Survey

to the

United States Department of Energy

under

Contract No. EY-76-C-05-5199

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Robert B. Erwin, Director

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ABSTRACT

A stratigraphic framework for the Middle and Upper Devonian clastic sequence in the subsurface of southern West Virginia was established using gamma-ray logs, drillers' logs, and sample descriptions. Lithostratigraphic units can be traced into the West Virginia subsurface from outcrops in New York and Ohio. The stratigraphic units recognized include the Marcellus Shale, Genesee Formation, Sonyea Formation, West Falls Formation, and Java Formation from the New York section and the Ohio Shale and Chagrin Shale from the Ohio section. The depositional environment of these strata is established as a shallow epicontinental sea with shelf-like platforms along its margins. The southern limit of the depositional basin lay in southern West Virginia in early Late Devonian time. The Devonian shale within the study area is, strictly speaking, submature with respect to hydrocarbon generation yet produces a high-quality gas. An interconnected fracture system is postulated to be the gas reservoir in which gas is believed to accumulate where there is the complimentary presence of both thick intervals of black shale and broad flexures which produce fractures. New areas of potential shale gas exploration for both the Huron Member of the Ohio Shale and the Rhinestreet Shale-Marcellus Shale interval are located east of the Warfield Anticline in Boone, Logan, Mingo, McDowell, Wyoming, and Raleigh Counties, West Virginia.

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INTRODUCTION

The sequence of Middle and Upper Devonian clastic rocks referred to as the "Devonian shale" has, for the most part, been overlooked since the earliest days of geologic research in West Virginia. In spite of the fact that these rocks produced natural gas as early as 1908 (Milton field, Cabell County), the detailed subsurface stratigraphic relationships of this interval were poorly known. With continued exploration for natural gas and the need to use all energy resources, it became evident that the stratigraphic relationships of the "Devonian shale" had to be delineated better so that the resource in these rocks could be more efficiently exploited. The purpose of this investigation, therefore, is to detail the stratigraphic relationships of the Middle and Upper Devonian clastic sequence in southern West Virginia and to evaluate its gas producing potential in terms of this stratigraphic framework.

The study area encompasses approximately 5000 square miles and includes the counties of Cabell, Wayne, Lincoln, Logan, Mingo, Boone, McDowell, Wyoming, Raleigh, Summers, Mercer, and Monroe (Figure 1). The area is roughly normal to the axis of the depositional basin and to the regional structure. Major structural features are illustrated in Figure 2. Of special importance to this study is the location of the Warfield Anticline and the Rome Trough. The Rome Trough is a basement feature (graben) whose boundaries are located at the approximate positions of the Warfield Anticline on the east and the next major anticline westward on the west. The Rome Trough does not appear to have affected sedimentation during the Late Devonian but may affect

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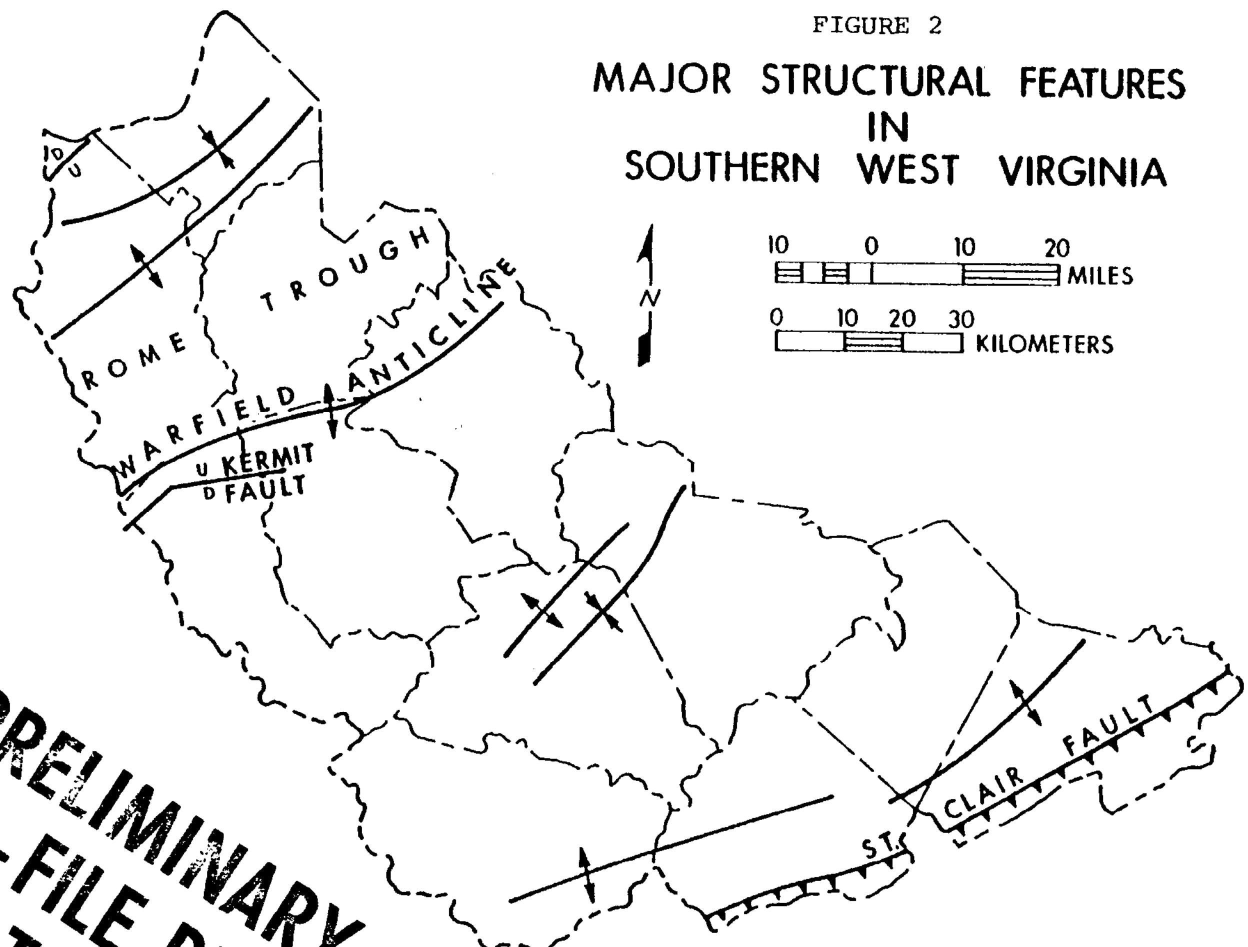
FIGURE 1 STUDY AREA.

FIGURE 2

MAJOR STRUCTURAL FEATURES IN SOUTHERN WEST VIRGINIA



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gas production.

The interval known as the "Devonian shale" occupies the stratigraphic position between the base of the Lower Mississippian Berea Sandstone and the top of the Middle Devonian Onondaga Limestone. In the westernmost part of the study area an additional Lower Mississippian formation beneath the Berea Sandstone, the Bedford Shale, can be recognized where the Upper Devonian Cleveland Member of the Ohio Shale is present. Where the Cleveland Member is absent, the Bedford Shale cannot be distinguished from the shale and siltstone of the Upper Devonian and thus is included in the undifferentiated "Devonian shale" interval. The thickness of the Middle and Upper Devonian clastic sequence ranges from just less than 1000 feet in the west to more than 4500 feet in the east (Figure 3).

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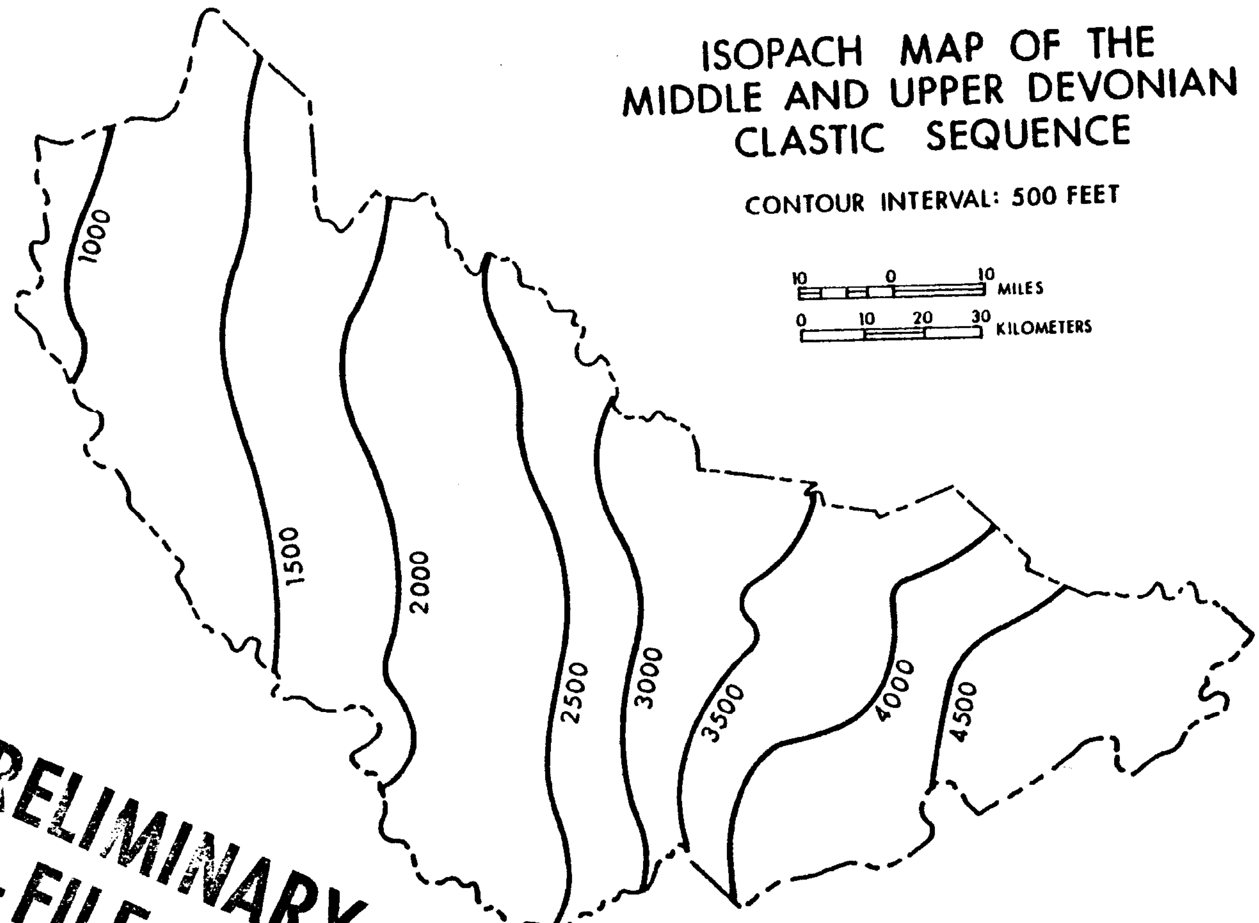
Early studies of the Devonian rocks in West Virginia are included in county geologic reports where Devonian rocks are exposed in outcrop. A supplemental study to the county reports is a compilation by Woodward (1943) of data on the Devonian of the entire state. This report is a compendium of the known stratigraphic and paleontologic information of the Devonian in West Virginia. Included are both outcrop data and the available subsurface data which were used to construct a series of very general maps and cross sections. After this report, very little work was done on the subsurface Devonian clastics other than referring to them as the "Devonian shale".

Almost thirty years later, Schwietering (1970) provided the first comprehensive study of the subsurface stratigraphy of this interval in the central and western portions of the Appalachian basin. Using

FIGURE 3

ISOPACH MAP OF THE MIDDLE AND UPPER DEVONIAN CLASTIC SEQUENCE

CONTOUR INTERVAL: 500 FEET



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gamma-ray logs, sample studies, and measured outcrop sections, Schwietering traced units recognized in outcrop in Ohio into the subsurface of eastern Ohio, western Pennsylvania, and northern West Virginia. The equivalence of New York nomenclature and Ohio nomenclature was established.

More recently, stratigraphic studies which included parts of this study area were those of Walls (1975); Patchen and Larese (1976); Bagnall and Ryan (1976); Provo, Kepferle, and Potter (1977); and Patchen (1977). Studies of a more economic nature included those of Dennison (1971); Harris, de Witt, and Colton (1978); and numerous papers in the proceedings volumes of the Eastern Gas Shales Symposiums (1977, 1978). The United States Geological Survey also has produced a series of preliminary cross sections across the basin (Wallace and others, 1977, 1978; Roen and others, 1978; and West, 1978) as part of the Eastern Gas Shales Project in cooperation with the geological surveys of New York, Pennsylvania, Ohio, West Virginia, Kentucky, and Tennessee.

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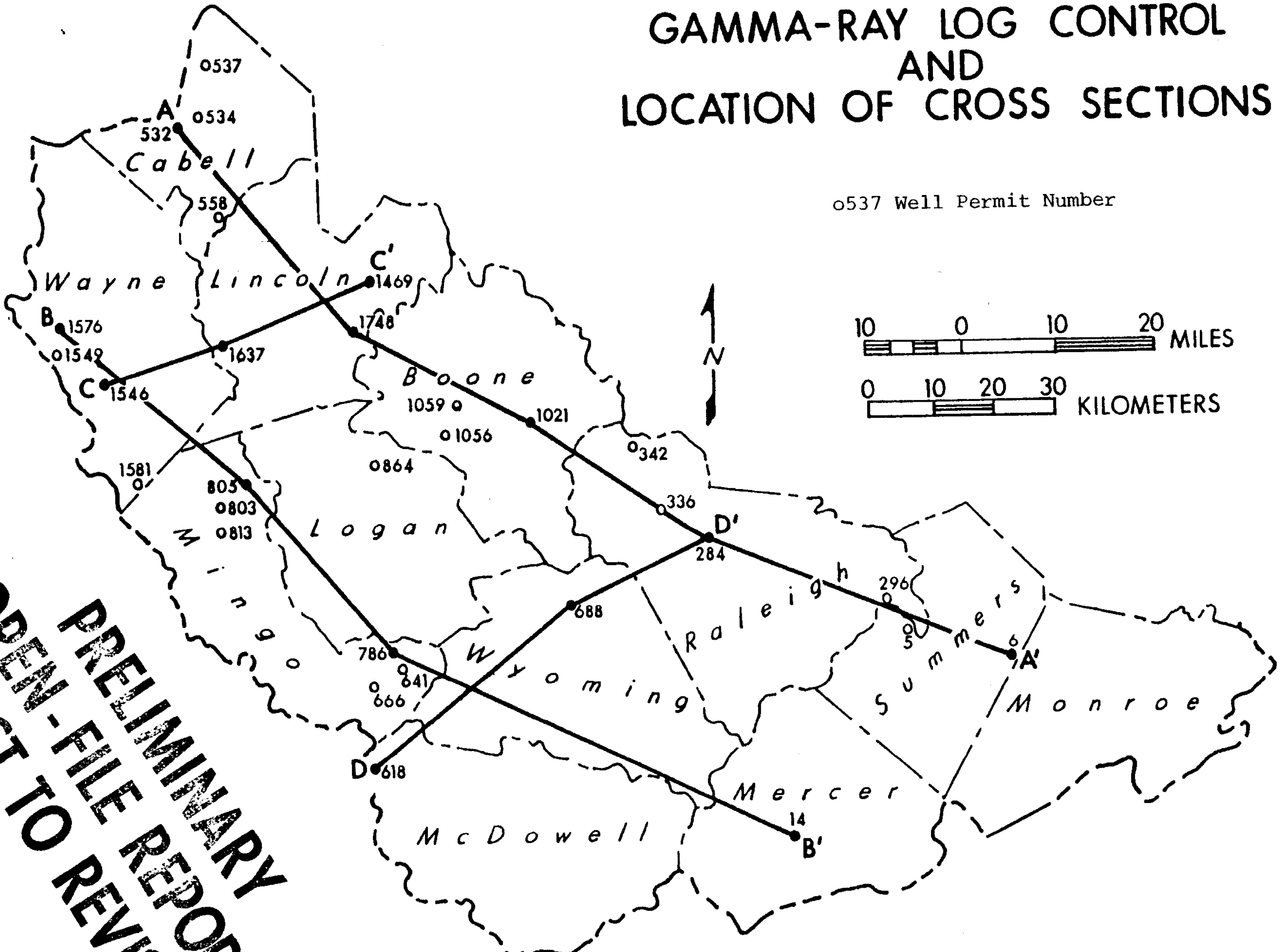
Stratigraphic data used in this study were derived from two cores taken in Lincoln County, West Virginia, gamma-ray logs from 29 wells which penetrated the entire clastic interval (Figure 4); 366 drillers' logs which include the entire interval (Plate 1); and numerous published and unpublished well sample descriptions. Gas production data were compiled from 224 wells in the study area. Geochemical analyses of 690 samples representing one core and well cuttings from 18 additional wells yielded elemental and mineralogical data. These data were generated by X-ray fluorescence and diffraction.

Figure 4

GAMMA-RAY LOG CONTROL AND LOCATION OF CROSS SECTIONS



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DEVONIAN SHALE STRATIGRAPHY

STRATIGRAPHIC FRAMEWORK

The stratigraphy of the Middle and Upper Devonian clastic sequence has been studied in outcrop in New York and Ohio throughout the last 150 years. From these well-exposed sections, a stratigraphic framework has been developed (Figure 5). Cycles consisting of a basal black shale overlain by gray shale, silty shale, and siltstone, and considered to be broad time-equivalent units, were recognized by Pepper, de Witt, and Colton (1956), Colton and de Witt (1958), and de Witt and Colton (1959) in western New York. Each cycle was considered a formation which could be traced laterally across the western portion of the basin. Early studies of the Devonian sequence in West Virginia, however, dealt primarily with the coarser facies found in outcrop in eastern parts of the state where the black shales similar to those used to define the western New York cycles were not found. County geologic reports were concerned only with these coarser facies and the nomenclature used for these rocks originated in eastern Pennsylvania and New York and was subsequently applied to the rocks in eastern West Virginia.

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In the subsurface of western West Virginia, where shale is the predominant lithology, Tucker (1936, 1944) and Martens (1945) referred to the interval as "Devonian shale" making no effort to subdivide it. Woodward (1943) attempted to correlate the rocks exposed in outcrop with those found in the subsurface, by loosely applying outcrop nomenclature to the subsurface rocks. However, for the most part, the rocks

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OHIO	VIRGINIA	PENNSYLVANIA / WEST VIRGINIA	NEW YORK		
BEREA SANDSTONE	POCONO FORMATION	POCONO FORMATION		MISSISSIPPIAN	
BEDFORD SHALE					
OHIO SHALE: CLEVELAND MEMBER	HAMPSHIRE FORMATION	HAMPSHIRE FORMATION	CONEWANGO GROUP	DEVONIAN	UPPER
OHIO SHALE: CHAGRIN SHALE	CHEMUNG FORMATION	CHEMUNG FORMATION	CONNEAUT GROUP		
OHIO SHALE: HURON MEMBER			CANADAWAY GROUP		
UPPER OLENTANGY SHALE	BRALLIER FORMATION	BRALLIER FORMATION	JAVA FORMATION		
			WEST FALLS FORMATION		
			SONYEA FORMATION		
	MILLBORO SHALE	HARRELL SHALE	GENESEE FORMATION		
LOWER OLENTANGY SHALE		TULLY LIMESTONE	TULLY LIMESTONE		MIDDLE
		MAHANTANGO FORMATION	MOSCOW FORMATION		
			LUDLOWVILLE FORMATION		
			SKANEATELES FORMATION		
		MARCELLUS SHALE	MARCELLUS SHALE		
DELAWARE LIMESTONE	ONONDAGA LIMESTONE / HUNTERSVILLE CHERT / NEEDMORE SHALE /	ONONDAGA FORMATION	ONONDAGA LIMESTONE		

FIGURE 5. STRATIGRAPHIC NOMENCLATURE FOR MIDDLE AND UPPER DEVONIAN ROCKS IN THE APPALACHIAN BASIN

in the subsurface continued to be referred to as "Devonian shale". Haught (1959) in a report on the oil and gas of southern West Virginia, and Cardwell and others (1970) and Cardwell (1977), in reports on the oil and gas fields of West Virginia, indicated the continued difficulty in subdividing the interval in the subsurface and referred to it as "Devonian shale".

In a study of the Devonian rocks of Ohio and their eastern equivalents, Schwietering (1970) recognized the presence of lithologic units in the subsurface of West Virginia correlative to rocks in outcrop in Ohio and Kentucky. Schwietering also showed the relationship of the Ohio nomenclature to that of the eastern West Virginia outcrop. A series of preliminary cross sections prepared by the United States Geological Survey as part of the resource characterization phase of the Eastern Gas Shales Project, which was initiated in FY 1977, suggested the correlation of the New York and Ohio sections with the subsurface Devonian rocks in West Virginia. Due to the location of these cross sections, however, areas remained where lateral continuity in all units is not maintained. Using these preliminary cross sections and additional data provided by the cooperating state geological surveys, I correlated the named stratigraphic units of the New York section from the outcrop areas in the north into the subsurface around the western periphery of the basin, to southern West Virginia. The resulting stratigraphic framework developed for use in the subsurface of West Virginia is based on a combination of Ohio and New York nomenclature (Figure 6). The upper part of the section which consists of the Ohio Shale and the Chagrin Shale is correlated with the Ohio out-

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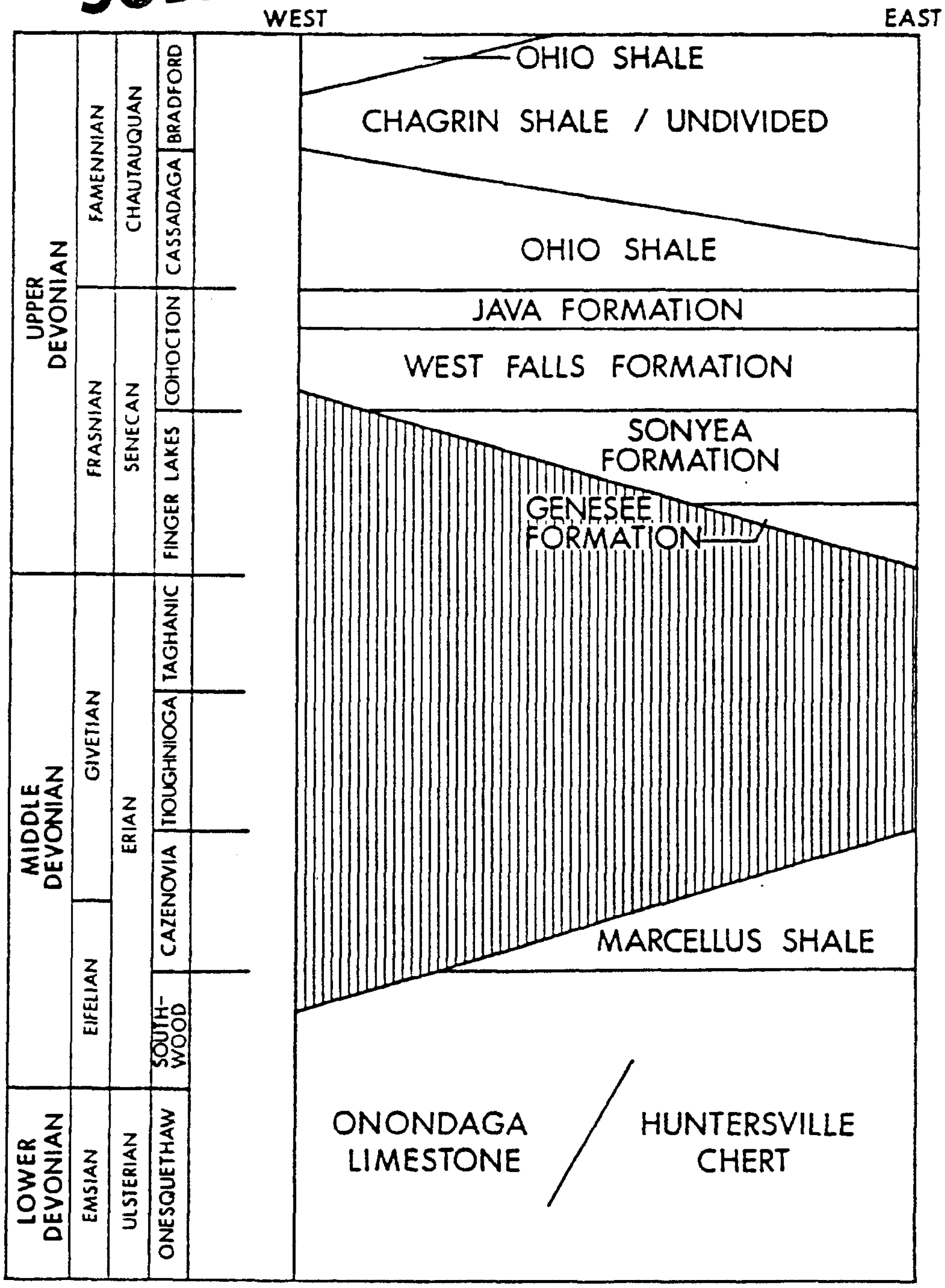

Figure 6. Stratigraphic nomenclature of Middle and Upper Devonian rocks in southern West Virginia.

crop. This is essentially the last major cycle similar to those recognized in New York. All units below the Ohio Shale are correlated with the New York section.

The terminology used in Virginia, Pennsylvania, and West Virginia for outcrops of Devonian rocks was developed almost exclusively for use in the eastern sandstone and siltstone facies and is not meaningful when dealing primarily with the western shale facies. A gross comparison of the eastern facies terminology with the nomenclature used in this study is illustrated in Figure 7. The Millboro facies represents the lowermost black shale interval which is comprised of the black shale of the Marcellus Shale, Geneseo Formation, Sonyea Formation, and the West Falls Formation (in part) where they converge and onlap the Onondaga Limestone. The Brallier interval is characterized by the gray and black shale and scattered siltstone between the upper part of the West Falls Formation and the Huron Member of the Ohio Shale, inclusive, in the west, and the gray shale and siltstone of the Sonyea Formation and the upper part of the West Falls Formation, inclusive, in the east. The Chemung facies is represented by the siltstone and gray shale of the Chagrin Shale in the west, and coarser eastern facies equivalents of the sequence between the uppermost West Falls Formation and the Ohio Shale, inclusive, in the east. The Catskill redbed facies is not present in the study area. The westward migration of these facies through time results in the presence of each facies farther west in progressively younger stratigraphic units. Boundaries between units of the eastern facies are not distinct and cannot readily be picked on wireline logs.

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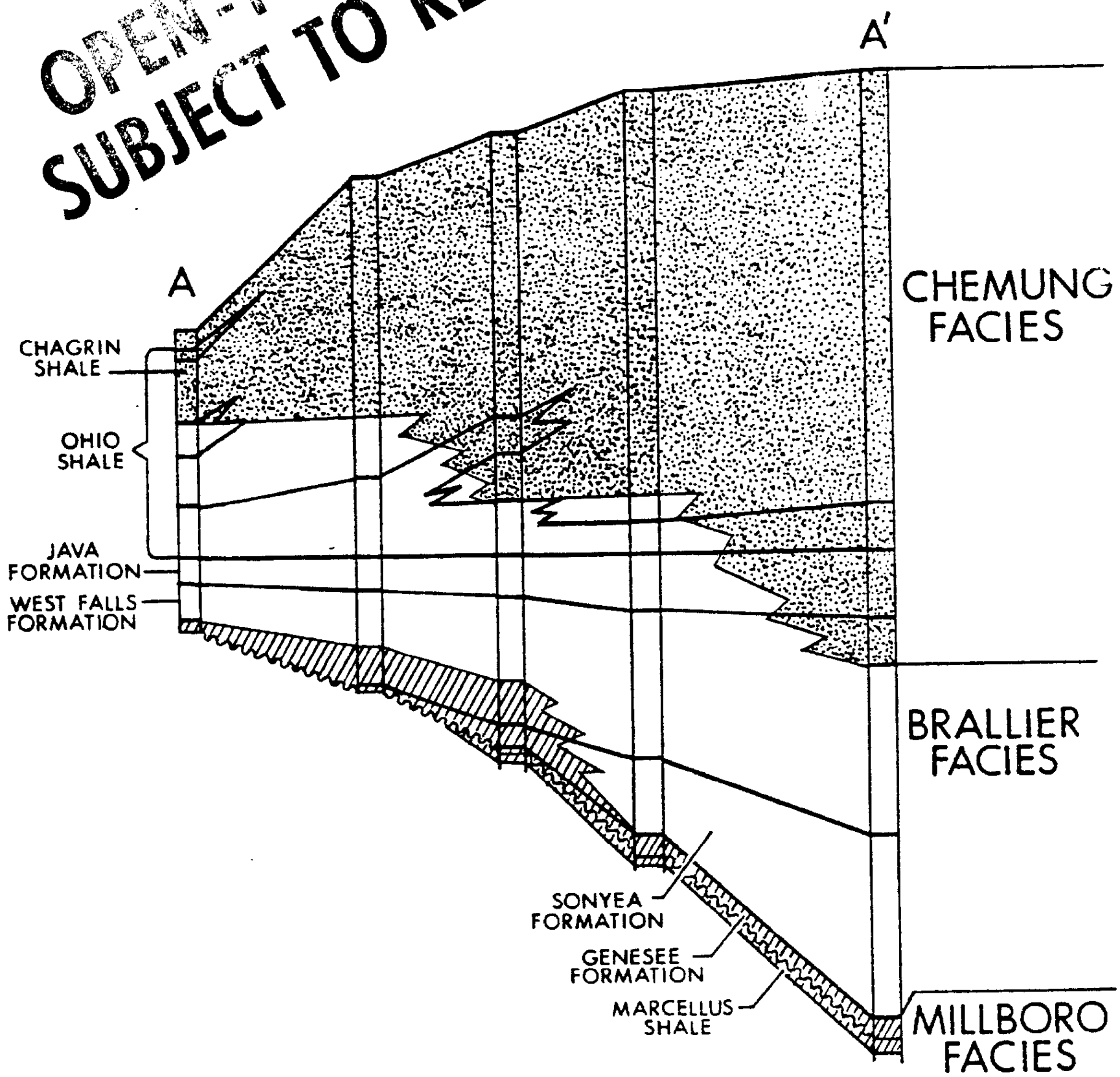

Figure 7. Relation of outcrop nomenclature to subsurface nomenclature.

The time-stratigraphic relationships illustrated in Figure 6 are supported in part by biostratigraphic studies of the conodonts (Duffield, 1978), ostracods (Warshauer, 1978), and palynomorphs (Clendening, personal communication). Units in southern West Virginia are only slightly diachronous when compared to the North American standard section in New York.

DESCRIPTIVE STRATIGRAPHY

Marcellus Shale

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The Marcellus Shale, named for exposures near Marcellus Village, Onondaga County, New York, was first described by James Hall (1839) as a black slaty shale with limestone nodules which overlies the Onondaga Limestone. The original description included Hamilton shale other than what is now considered Marcellus Shale. Clarke and Luther (1904) restricted the usage of the name to the lowermost black shale in the interval. The U.S. Geological Survey and the New York Geological Survey (Rickard, 1975) recognize the Marcellus Shale as the lowest formation in the Hamilton Group.

In southern West Virginia, the Marcellus Shale is the only formation of the Hamilton Group that I recognize. It is a black calcareous shale which conformably overlies the Onondaga Limestone or the Huntersville Chert. The Marcellus Shale is bounded at the top by an unconformity and is onlapped progressively to the west by the Genesee Formation, Sonyea Formation, and the West Falls Formation.

The distribution and thickness of the Marcellus Shale is represented on Plate 2. From the north-south trending isoline in the western half of the study area, the shale is recognized to the east as having a uniform distribution generally between 20 and 30 feet thick. There is very little variation in thickness in a very large portion of the study area. The characteristic gamma-ray log signature of the Marcellus Shale is typically of very high natural radioactivity relative to that of bounding formations (Figure 8). The gamma-ray log signature typically shows two or three spikes, decreasing in number to the west, as the unconformity at its upper boundary has removed more of the formation.

Genesee Formation

The first depositional cycle recognized above the Tully Limestone in New York is identified as the Genesee Formation. This unit was first described by Vanuxem in 1842 for exposures along the Genesee River north of Portageville, New York. The formation includes all rocks between the base of the Sonyea Formation and the top of the Tully Limestone, or in areas where the Tully is absent, the Hamilton Group. It was subdivided into several members by de Witt and Colton (1959). In the westernmost exposures of the Genesee Formation four members are recognized: the Geneseo Shale (black shale), Penn Yan Shale (dark gray shale with thin interbeds of black shale), Genundewa Limestone, and the West River Shale (dark gray shale). Farther to the east, six members are recognized: the Geneseo Shale, Penn Yan Shale, Sherburne Flagstone (silty shale and siltstone), Renwick Shale (black shale), Ithaca Member (sandstone, siltstone, silty mudrock), and West River Shale Members. The complexities of the Genesee stratigraphy in New York are not found in southern West Virginia. I can recognize

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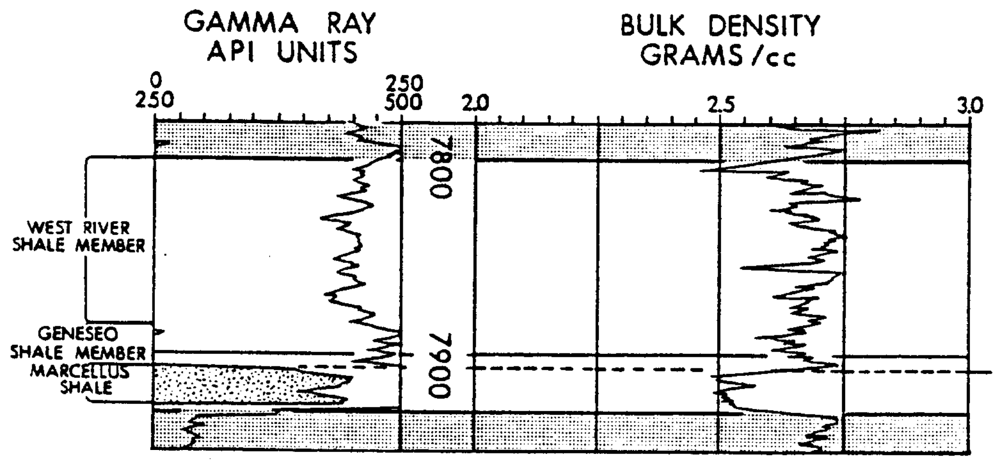

Figure 8. Typical gamma-ray log of the Genesee Formation and the Marcellus Shale in southern West Virginia. (Raleigh 296)

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only two of the seven named stratigraphic units in the study area, the Geneseo Shale Member and the West River Shale Member. The distribution and thickness of the Genesee Formation and its members are presented in Plate 2.

The Geneseo Shale Member, the basal member of the formation, is a black to medium-dark-gray pyritic shale with some minor olive-gray to black siltstone. The gamma-ray log signature (Figure 8) shows that the Geneseo Shale Member has a higher radioactivity than the overlying West River Shale Member but is substantially lower than the underlying Marcellus Shale. The contact between the Geneseo Shale Member and the Marcellus Shale is not easily recognized in the local section as the contact is unconformable and no other Hamilton Group shale is present. Only by tracing the units from the north where intervening units can be recognized can individual subtleties allow the two shales to be distinguished one from another. The Geneseo Shale Member occurs only in the northeast part of the study area and ranges from zero to slightly more than 30 feet thick.

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There has been some question as to the identification of the Geneseo Shale Member and whether or not the black shale overlying the Marcellus in the study area may be a black shale of the Penn Yan Shale. Such a correlation is, of course, possible. However, after examination of the stratigraphic cross sections of West (1978), I concluded that the Penn Yan Shale pinches out in northern West Virginia between the West River and the Geneseo Shale Members and the black shale of the Geneseo Shale Member extends to southern West Virginia.

The West River Shale Member, the upper unit of the Genesee cycle, is represented in southern West Virginia by a medium-dark to dark-gray shale with olive-gray siltstone. The gamma-ray log signature shows the West River Shale to be less radioactive than either the overlying Middlesex Shale Member of the Sonyea Formation or the underlying Geneseo Shale Member. The West River Shale ranges in thickness from zero to more than 100 feet with a broad expanse of shale ranging from 20 to 40 feet in the west. The greatest thickness is located in a linear trough in Summers and Mercer Counties (Plate 2).

Sonyea Formation

The next cycle recognized is that of the Sonyea Formation which was first defined by Chadwick in 1933 for exposures in Cashaqua Creek which flows through Sonyea, New York. This formation was established by grouping two previously recognized stratigraphic units, the Middlesex Shale (black shale) and the Cashaqua Shale (gray shale and dark gray siltstone). It was subdivided into several members by Colton and de Witt (1958), who recognized two additional units, the Pulteney Shale and the Rock Stream Siltstone, both of which are better developed east of the type area. I can trace only two members into southern West Virginia, the Middlesex Shale Member and the Cashaqua Shale Member. The Middlesex Shale Member is a medium-dark to dark-gray shale with a thickness ranging from zero to more than 30 feet (Plate 3). It is the basal black shale of the depositional cycle. The gamma-ray log signature is rather distinctive in southern West Virginia having a characteristic two-pronged spike (Figure 9).

The Middlesex Shale Member is overlain by a thick sequence of

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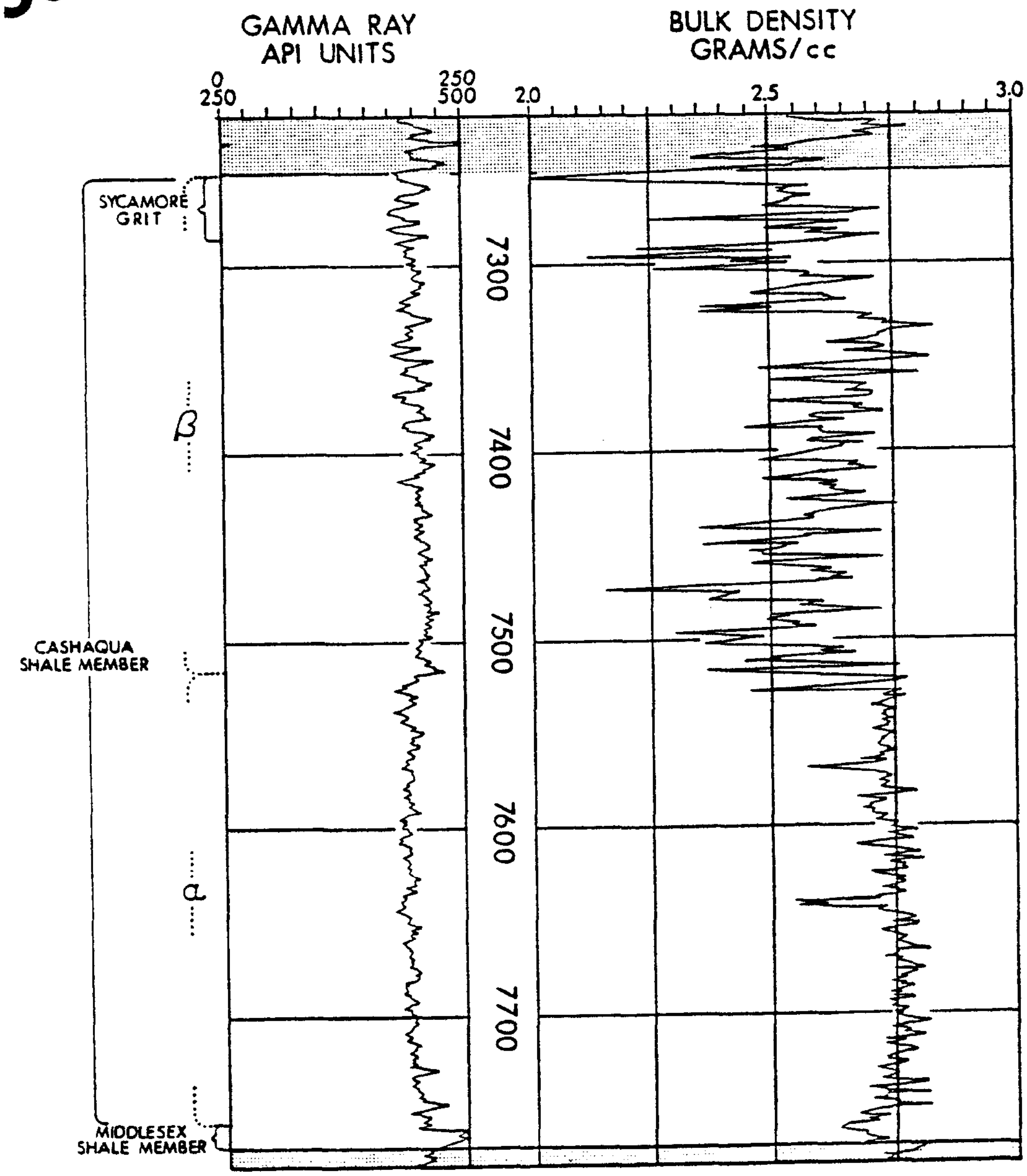

Figure 9. Typical gamma-ray log of the Sonyea Formation in southern West Virginia. (Raleigh 296)

shale and siltstone, the Cashaqua Shale Member. The gamma-ray log signature of this unit also is very distinctive. Two intervals, informally identified as beds α and β , are recognized. Bed α has a considerably lower radioactivity than either the Middlesex Shale Member below or bed β above. Bed α of the Cashaqua Shale Member consists of medium-dark to dark-gray shale with olive-gray to olive-black siltstone interspersed. It ranges in thickness from zero to more than 200 feet. The boundary between beds α and β is marked by a conspicuous shift from lower (bed α) to higher (bed β) radioactivity which can be seen throughout the study area. Bed β is composed of interbedded medium-dark-gray to grayish-black shale and olive-gray to medium-dark-gray siltstone. Thickness of this unit ranges from zero to more than 600 feet. The upper boundary of bed β , and consequently of the Sonyea Formation, is placed at the top of a prominent siltstone tentatively identified as the drillers' "Sycamore Grit".

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West Falls Formation

The West Falls Formation was first defined by Pepper, de Witt, and Colton (1956) from exposures along Cazenovia Creek in the vicinity of West Falls and East Aurora, central Erie County, New York. Six members were recognized, bounded by the black shale of the Rhinestreet Shale Member at the base and the Nunda Sandstone at the top. Most members above the Rhinestreet contain varying amounts of gray silty shale and siltstone. In West Virginia I recognize two units, the Rhinestreet Shale Member, a basal black shale, and the overlying Angola Shale Member, a gray silty shale with scattered siltstone.

The Angola Shale Member is a western shale facies of the Nunda Sandstone in New York. The West Falls Formation can be found throughout the entire study area and ranges in thickness from slightly less than 100 feet to more than 700 feet (Plate 4). In the southwest part of the study area, the Rhinestreet Shale Member is a massive black, pyritic shale with minor amounts of siltstone, and has a typical massive high radioactive log signature (Figure 10). In the southeast, this unit is composed of grayish-black to black, slightly pyritic shale and an increasing amount of medium-gray to olive-gray siltstone; the gamma-ray log signature (Figure 11), like that of Figure 10, indicates that in the southeast the Rhinestreet Shale Member is still characterized by higher radioactivities than its bounding units but the difference is less pronounced. The Rhinestreet Shale Member ranges in thickness from less than 100 feet in the west to more than 400 feet in the east. There is a thickening south of the Kermit Fault in northern Mingo County which indicates growth and differential sedimentation during Rhinestreet time. The area of thickest accumulation shifted west of the axis of the greatest accumulation of the older Devonian clastics during this time.

The Angola Shale Member is characterized by two subunits, α and β. Bed α is a sequence of interbedded medium-light to medium-dark-gray siltstone and medium-dark to dark-gray shale. The character of the gamma-ray log signature can be seen on Figures 10 and 12. The thickness of bed α of the Angola Shale Member (Plate 4) ranges from less than 50 feet to more than 250 feet. Bed β is composed primarily of olive-gray to medium-dark-gray, slightly calcareous, shaly siltstone.

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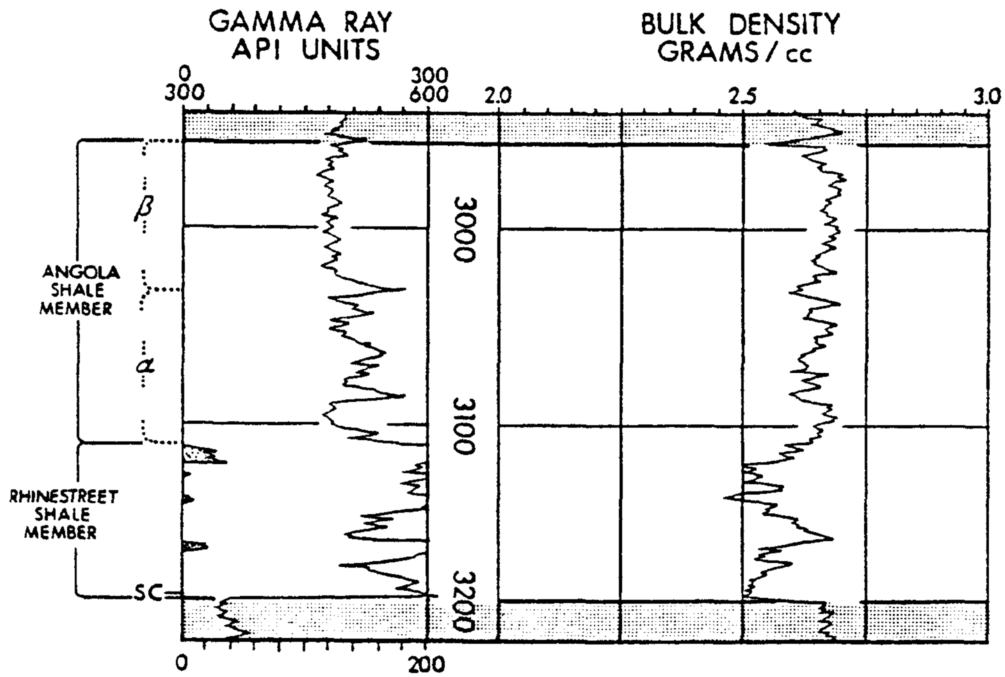

Figure 10. Typical gamma-ray log of the West Falls Formation in southwestern West Virginia. West Falls Formation overlies the Onondaga Limestone in this well. (Wayne 1581)

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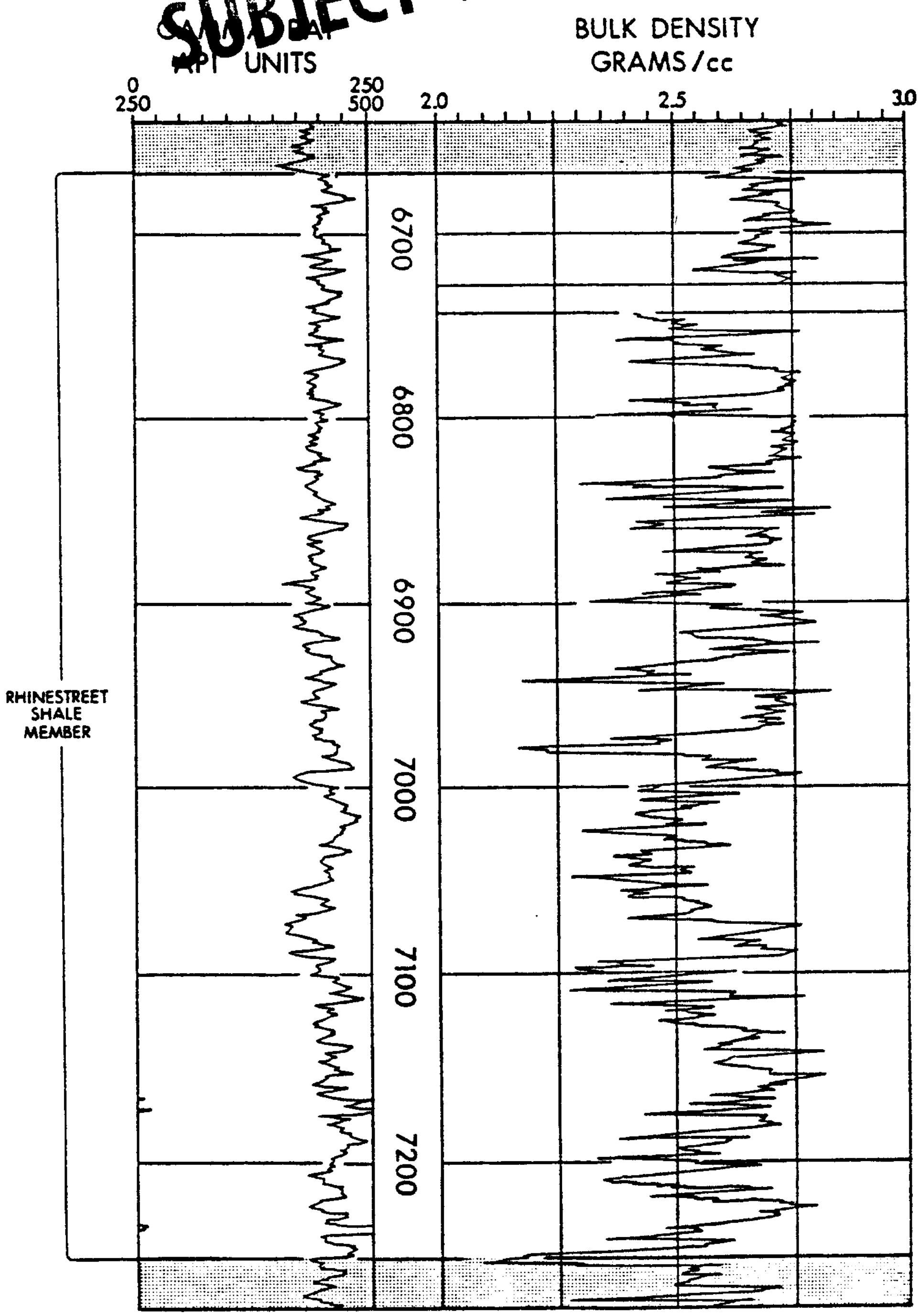

Figure 11. Typical gamma-ray log of the Rhinestreet Shale Member of the West Falls Formation in southeastern West Virginia. West Falls Formation overlies the Sonyea Formation in this well. (Raleigh 296)

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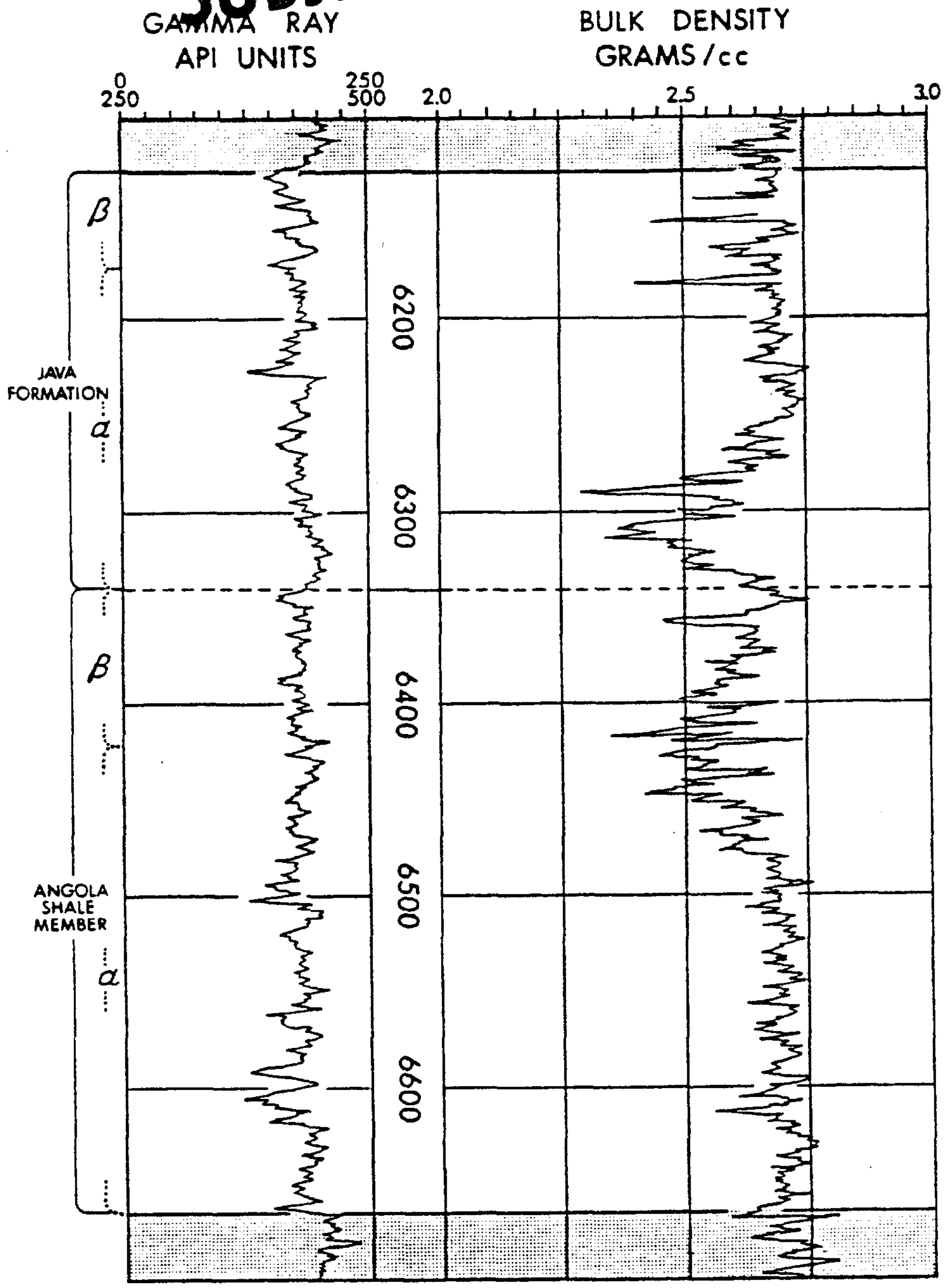

Figure 12. Typical gamma-ray log of the Angola Shale Member of the West Falls Formation and the Java Formation in southeastern West Virginia. (Raleigh 296)

The relatively low radioactive nature of the log signature and the lower density is characteristic of this unit. The thickness of bed β ranges from less than 40 feet to more than 120 feet. There is some suggestion of growth along the Kermit Fault as in the Rhinestreet Shale Member. The greatest thickness of bed β is in the same position as that of the Rhinestreet Shale Member.

Java Formation

The Java Formation was first described by de Witt in 1960 for exposures along Beaver Meadow Creek in Java Village and named for Java Township, Wyoming County, New York. Three members were recognized: the Pipe Creek Shale (black shale), the Hanover Shale (gray shale), and the Wiscoy Sandstone. The black Dunkirk Shale overlies the Java Formation at the type section. In West Virginia I can identify the formation rather easily but cannot readily subdivide it. In southern West Virginia, the Java Formation is a dark-gray to grayish-black shale with abundant olive-gray to medium-dark-gray, calcareous siltstone. The formation ranges in thickness from less than 100 feet to more than 240 feet. There is evidence of growth along the Kermit Fault. The base of the Java Formation is defined in the subsurface by the basal low density kick of the black Pipe Creek Shale marker, which can be seen to some extent across the basin (Figures 12 and 13). Two informal subdivisions of the Java are identified which do not correspond to members recognized in the New York section. The lower is bed α, an interval of interbedded shale and siltstone that ranges in thickness from 60 to 200 feet. The upper unit, bed β, is a 30 to

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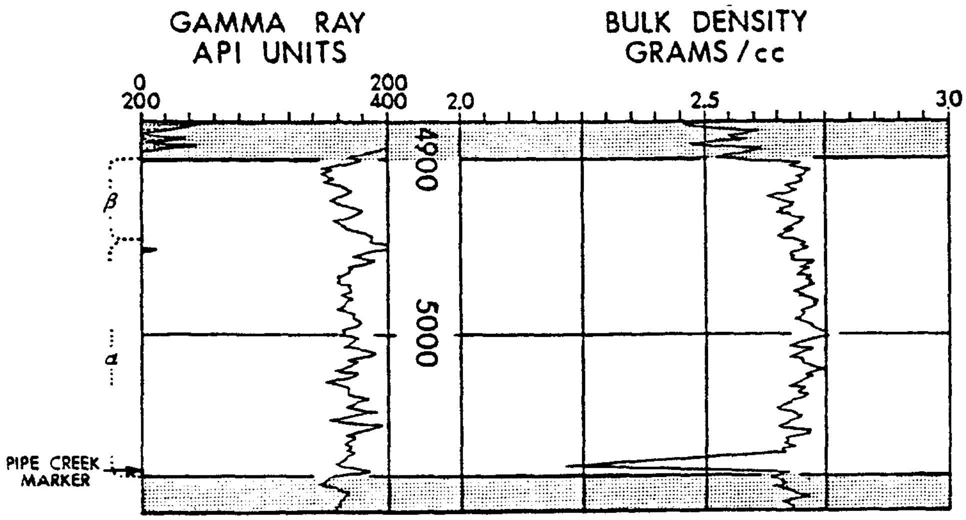

Figure 13. Typical gamma-ray log of the Java Formation in southwestern West Virginia. (Boone 1021)

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55 foot thick calcareous siltstone which in southwestern West Virginia has a conspicuous lower radioactivity than the overlying Huron Member of the Ohio Shale.

Ohio Shale

The Ohio Shale was first described by E.B. Andrews in 1870 from exposures in southern Ohio as a black bituminous shale. Throughout most of Ohio and eastern Kentucky the Ohio Shale is a dark-brown to black silty shale. The basal part of the Huron Member of the Ohio Shale correlates with the Dunkirk Shale of New York. In southern West Virginia, the Ohio Shale is a grayish-black to black, pyritic, silty shale which ranges in thickness from less than 200 feet in the east to more than 800 feet in the western part of the study area (Plate 6). Two subdivisions are recognized, the Huron Member and the Cleveland Member, separated by the Chagrin Shale. The gamma-ray log character (Figures 14, 15, and 16) shows the relatively higher radioactivity of the black Ohio Shale relative to that of the Java Formation and the Chagrin Shale. The lower part of the Huron Member is represented by a massive interval of highly radioactive black shale with increasing interbeds of lower radioactive gray shale near the top of the unit (Figure 14). In the southeastern part of the study area, the dilution of the black shale by the introduction of an increasing number of less radioactive shale interbeds results in a log character which is overall lower in radioactivity than what is found to the west. The radioactivity, however, is still greater in the Huron Member than in either the Java Formation below or the less radioactive facies above

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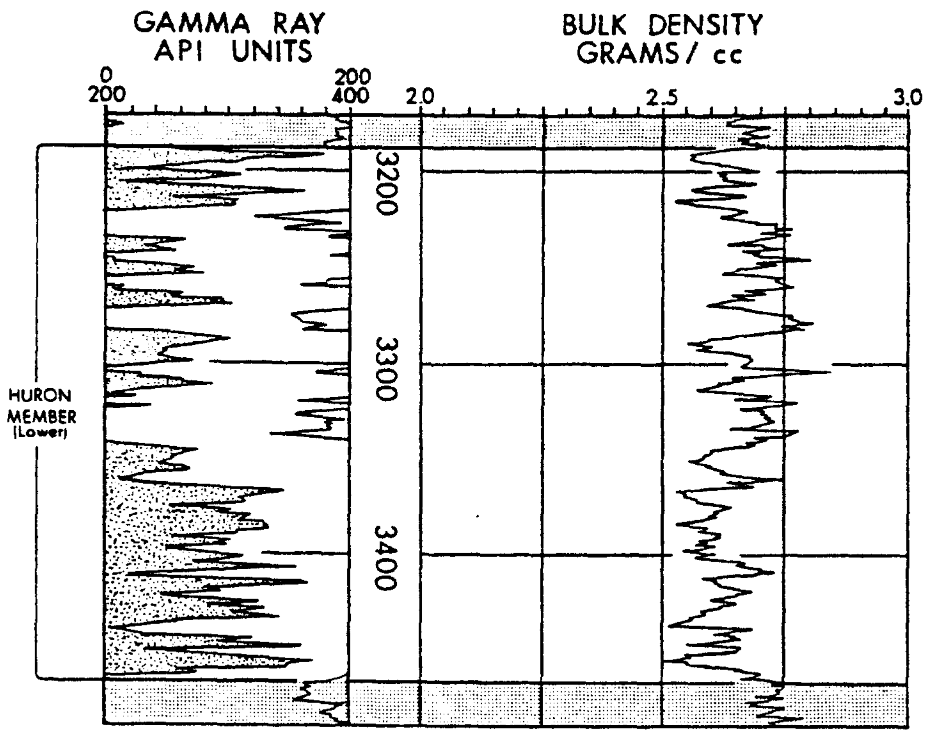

Figure 14. Typical gamma-ray log of the Huron Member of the Ohio Shale in southwestern West Virginia. (Lincoln 1421)

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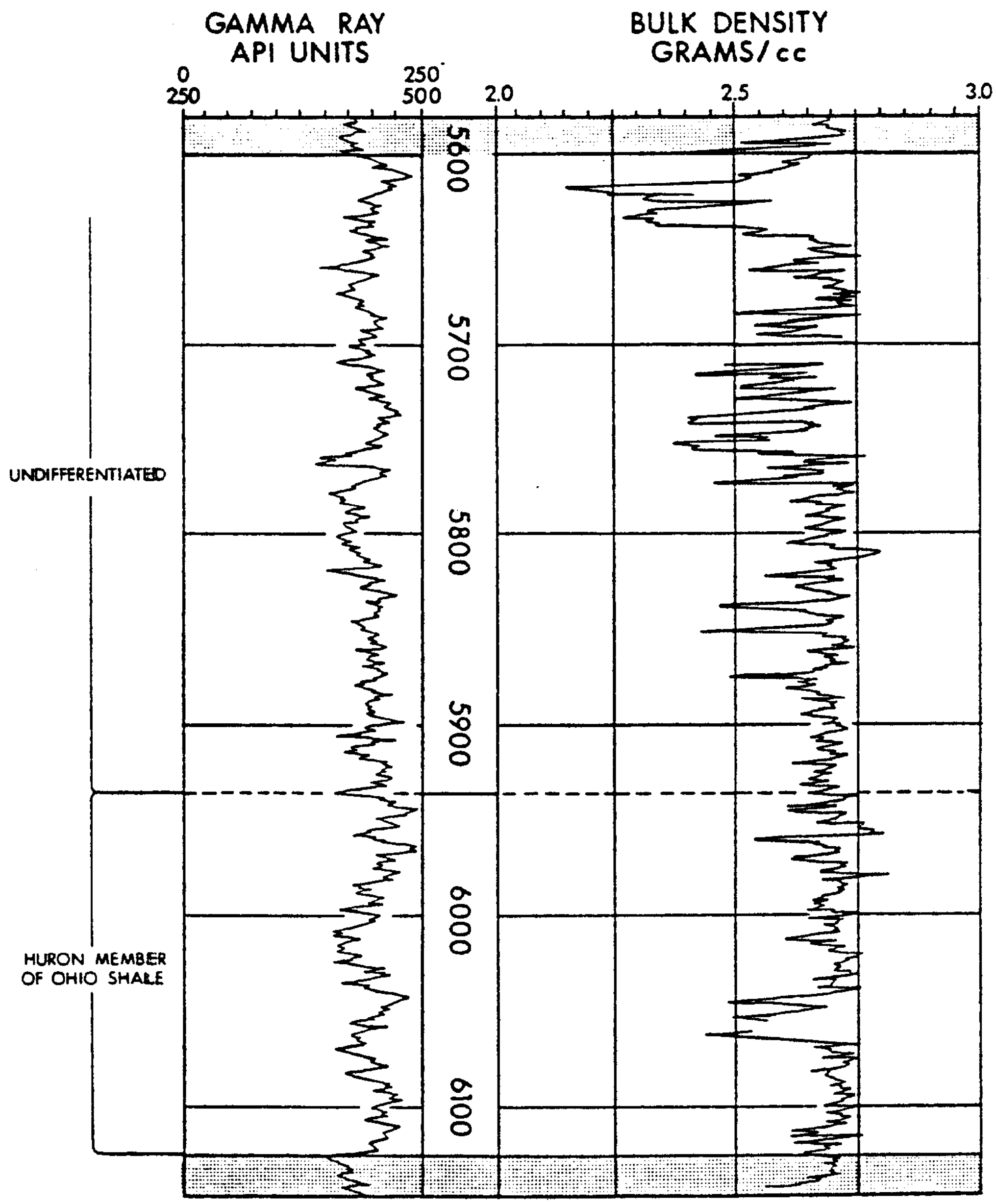

Figure 15. Typical gamma-ray log of the Huron Member of the Ohio Shale in southeastern West Virginia. (Raleigh 296)

(Figure 15).

The interval identified as the upper part of the Huron Shale (Figure 16) is a tongue of black shale which originates in the main black shale body to the west and thins to the east. This tongue is separated from the lower part of the Huron Member by a tongue of gray silty shale which thins to the west and eventually pinches out in the black shale of the Huron Member. The lower part of the Huron also is split by tongues of gray silty shale. As a result, the interval thins to the east where the black shale of the Huron Member intertongues with, and feathers out in, gray silty shale. The isopach map of the Huron Member of the Ohio Shale (Plate 6) includes the entire interval from the top of the upper tongue of the Huron Member in the west to the base of the lower massive tongue of the unit. The range in thickness is from less than 200 feet in the east to more than 800 feet locally in the northwest.

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The Cleveland Member of the Ohio Shale is the eastward extension of the youngest major tongue of the Ohio Shale. In southwestern West Virginia it thins from 150 feet in the west to a feather edge where it pinches out between the Bedford Shale and the Chagrin Shale.

Chagrin Shale and Eastern Facies

The Chagrin Shale was named by Prosser (1903) from exposures of gray shale and thin sandstone along the Chagrin River in northern Ohio which occupy the interval between the Cleveland and Huron Members of the Ohio Shale. In West Virginia the Chagrin Shale is easily recognized where both the Cleveland and Huron Members of the Ohio Shale

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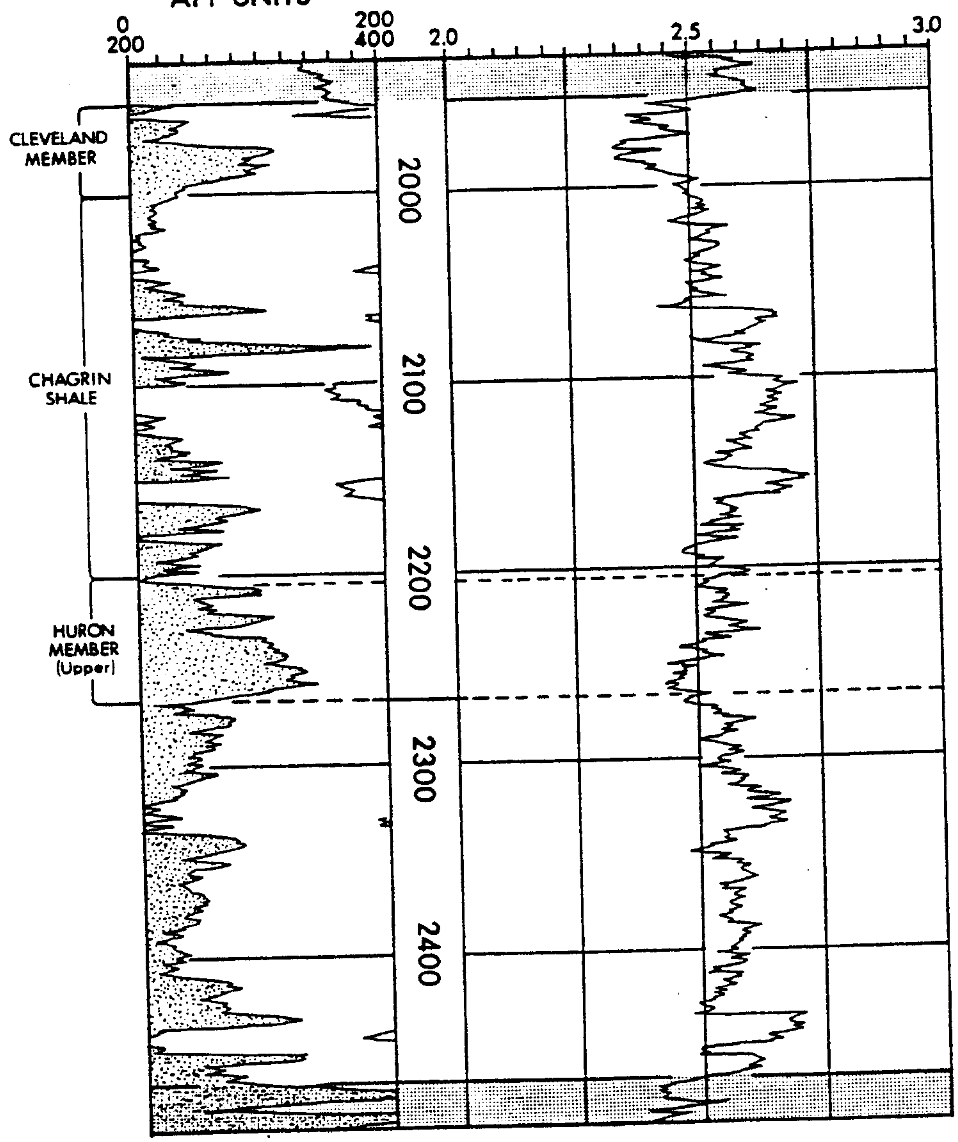

Figure 16. Typical gamma-ray log of the Cleveland Member of the Ohio Shale, the Chagrin Shale, and the upper part of the Huron Member of the Ohio Shale. (Wayne 1546)

are present but cannot be readily separated from coarser eastern equivalents. In southern West Virginia, the Chagrin Shale is composed of gray silty shale and medium-light-gray siltstone. Contacts are indistinct due to the vast amount of intertonguing between the Ohio and Chagrin Shales. Where the Cleveland Member is absent, the gray shale and siltstone above the Huron Member of the Ohio Shale is lumped together under the general heading of undifferentiated eastern facies. This interval also includes the eastern gray shale and thin siltstone facies of the Bedford Shale which is found stratigraphically between the Cleveland Member of the Ohio Shale and the Berea Sandstone in much of east-central Ohio and other non-black facies of the Ohio Shale. The eastern facies and the Chagrin Shale are included on one isopach map (Plate 6) because no distinct division exists between these facies. The entire interval ranges from 200 to 2000 feet in thickness.

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CROSS SECTIONS

Four interconnecting stratigraphic cross sections were constructed to show the lateral and vertical relationships of the Middle and Upper Devonian clastic sequence. The lines of section are indicated on Figure 4 and represent essentially two east-west dip sections (Plates 7 and 8) and two north-south strike sections (Plates 9 and 10). Datum for all sections is the sharp basal contact of the Huron Member of the Ohio Shale which can be recognized consistantly on gamma-ray and bulk density logs, in cores, and in well samples, across the entire area.

Plate 7 (section A-A') is the northernmost east-west dip section. On this section all stratigraphic units recognized in the study area can be identified. At the base of the section a major unconformity can be seen between Middle and Upper Devonian rocks. Physical evidence for the unconformity can be seen in a core from a Lincoln County, West Virginia, well (Permit Number Lincoln 1637), where a thin lag concentration of broken calcareous fossils in a matrix of black mudstone lies on the Onondaga surface. This represents reworking of sediments along the erosional surface of the unconformity. Paleontologic evidence also demonstrates a hiatus in the time-stratigraphic record. Duffield (1978) found lower Upper Devonian conodonts above the unconformity and lower Middle Devonian conodonts below in the carbonate rocks of the Onondaga Limestone. The unconformity was subsequently traced to the east where it is present at the top of the remaining Marcellus Shale interval. The progressive onlapping of the unconformity by the Genesee, Sonyea, and West Falls Formations is shown on Plate 7.

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The cyclic nature of the formations, with a basal high radioactive black shale overlain by less radioactive gray shale and siltstone, is best seen in the interval between the base of the Ohio Shale and the Middle-Upper Devonian unconformity. Four conspicuous cycles, each representing a formation, are recognized; however, the boundaries between formations (cycles) are not as prominent in the east as in the west. This is primarily due to the eastward decrease in the volume of radioactive black shale and the corresponding increase in the volume of gray shale and siltstone. The last major cycle in the Upper Devonian is the Ohio Shale and the overlying undifferentiated gray shale and siltstone. Of special note is the splitting of the massive black shale of the Huron Member eastward by wedges of gray silty shale and the westward thickening of the main body of massive high radioactive shale.

Plate 8 is the southern dip section B-B'. There is little difference between this section and section A-A', although a slight thinning is noticed especially in the pre-Ohio Shale sequence in this section. The Cleveland Member of the Ohio Shale is better developed in this section and there is less of a major split in the Huron Member and more of an interbedding of black and non-black shale. Section C-C' represents the westward strike section and section D-D' represents the eastern strike section (Plate 10). The most conspicuous difference between these sections is the loss of black shale (highly radioactive) units above the lower part of the Huron Member in the eastern section as well as the addition of units below the Rhinestreet Shale Member of the West Falls Formation.

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Siltstone of turbidite and deltaic origin is the main exploration target of gas companies in northern West Virginia. Gas has not yet been found in commercial volumes in the southern part of the state; however, the siltstone is there and should be explored. Two cross sections were constructed to illustrate the distribution of the siltstone packets in two different parts of the section (Figures 17 and 19). Figure 17 shows the distribution of several siltstone packets in the lower part of the section in the West Falls and Java Formations in the southeastern part of the state. The distribution pattern appears to represent turbidite fans originating northeast of the study area (Figure 18); however, details of their internal stratigraphy and

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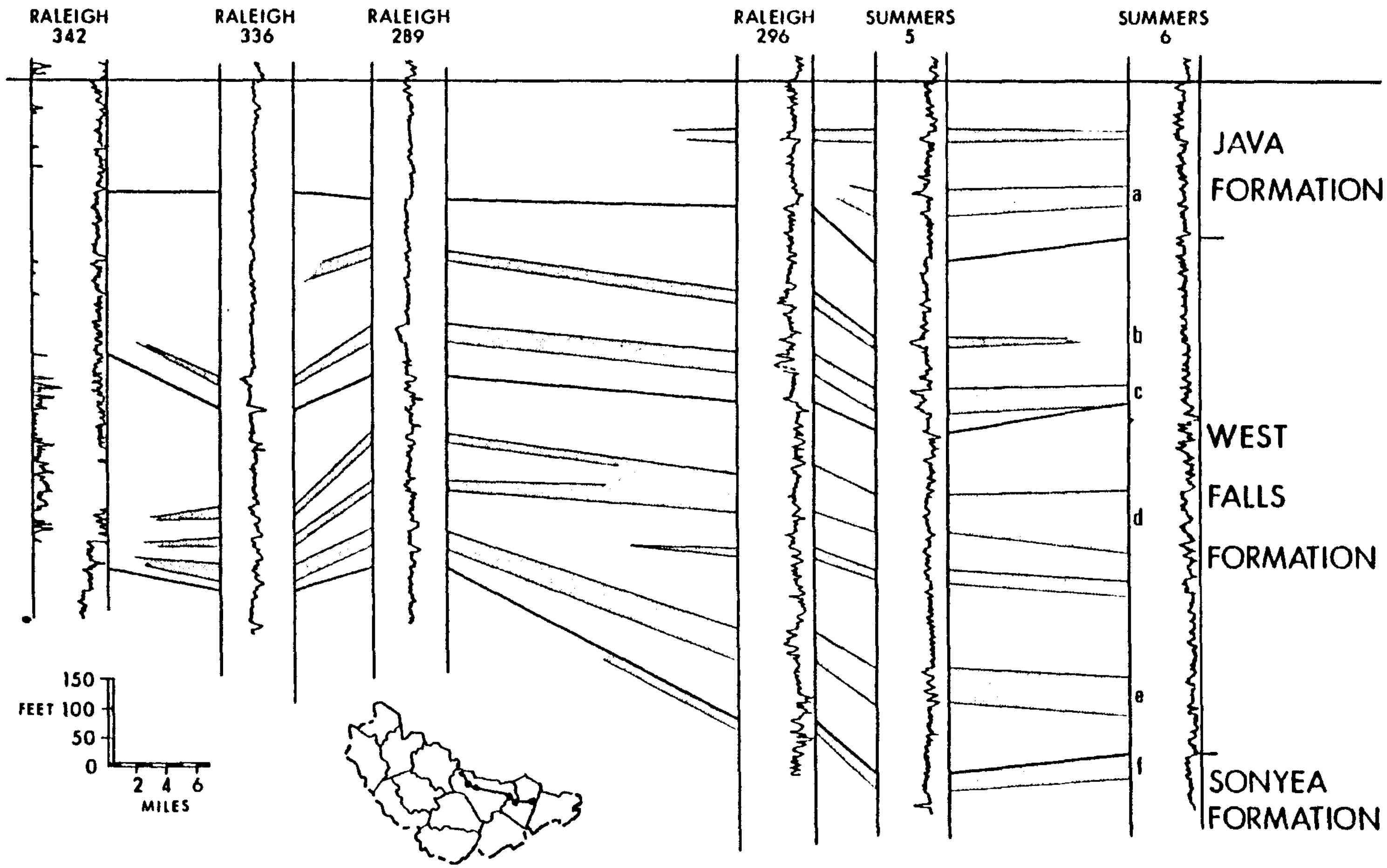

Figure 17. Gamma-ray log cross section showing the distribution of siltstones in the Java and West Falls Formations.

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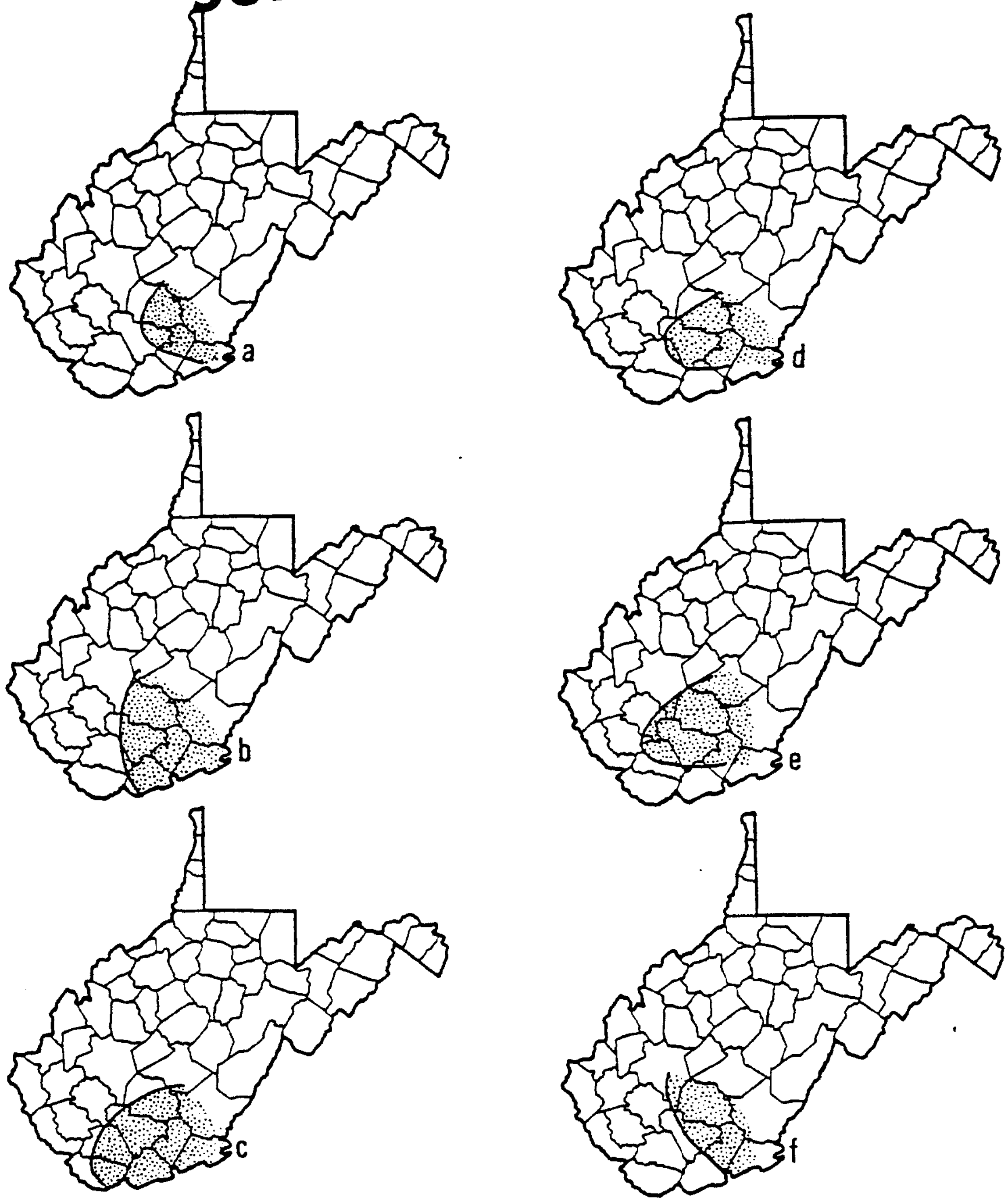

Figure 18. Lateral distribution of turbiditic siltstones in southeastern West Virginia.

specific lithologic character are not available due to the paucity of data from this area.

A second area of interest concerning the correlation of the shale section and the siltstone of the eastern facies is found in the upper part of the section in the western part of the study area. Figure 19 illustrates the relationship of several extensive siltstones to the black shale of the upper part of the Huron Member and the Cleveland Member of the Ohio Shale. A siltstone, or rather a packet of siltstone, tentatively correlated with the Fifth sand north of the study area is located immediately beneath the upper tongue of the Huron Shale in this area. The base of the Fifth sand is commonly used as the base of the Catskill Formation in the subsurface of northern West Virginia. If this siltstone is indeed the Fifth, then the interval between the base of the upper tongue of the Huron Shale and the top of the Cleveland Shale represents the distal offshore facies equivalent to the Catskill redbeds in northern and central West Virginia.

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GEOLOGIC HISTORY AND DEPOSITIONAL ENVIRONMENT

The geologic history of the southern part of the Appalachian basin during the latter half of the Devonian Period is one of orogeny and the response of sedimentation to this tectonic event. Two major unconformities of regional extent represent the orogenic phase. It is the younger of these unconformities, the Acadian Discontinuity of Wheeler (1963a, 1963b), that is found in the basal part of the interval under investigation. The paleogeology of the unconformity surface is illustrated in Figure 20. Progressively older units are exposed to

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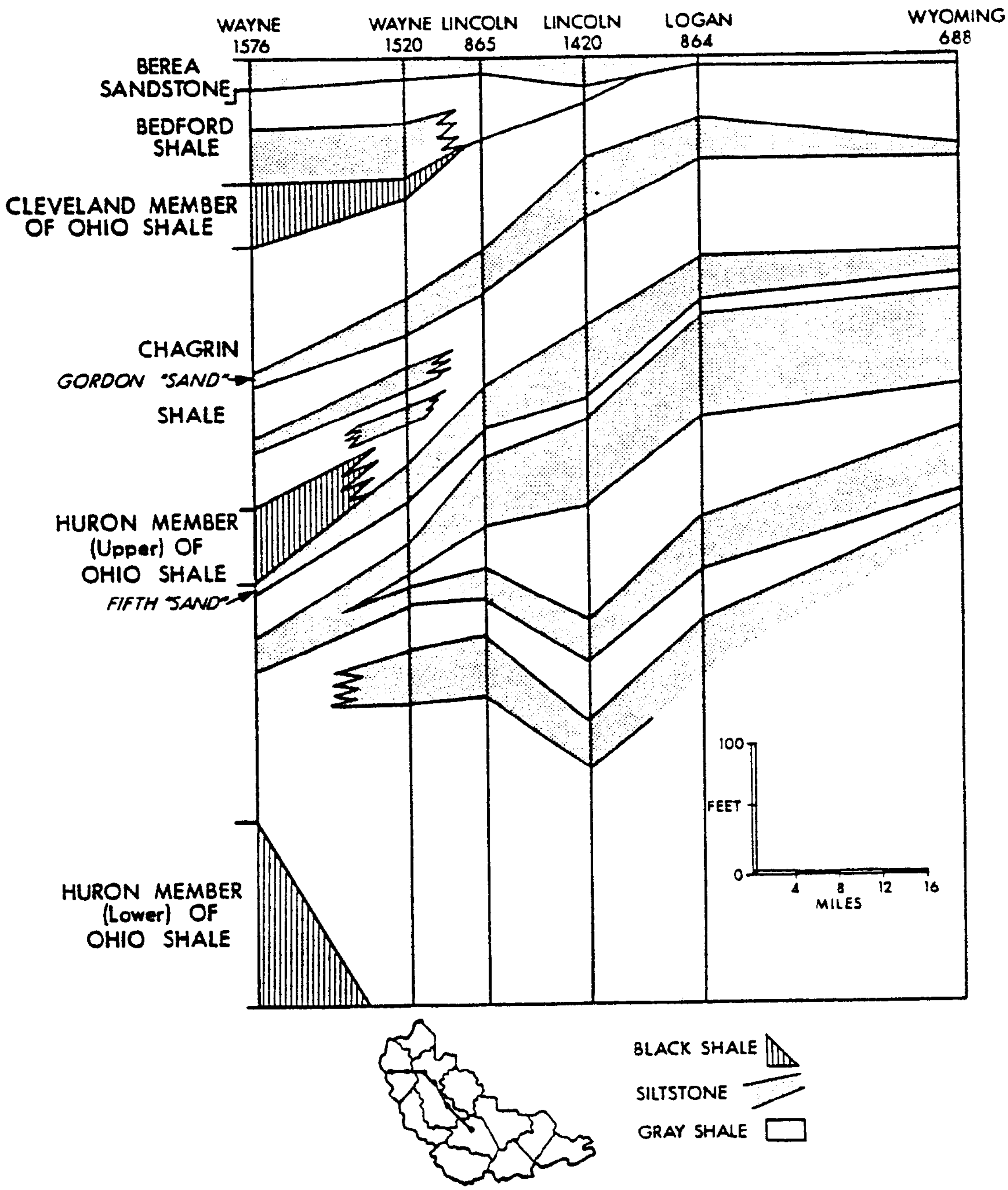

Figure 19. Cross section showing distribution of siltstones in the upper part of the section in southwestern West Virginia.

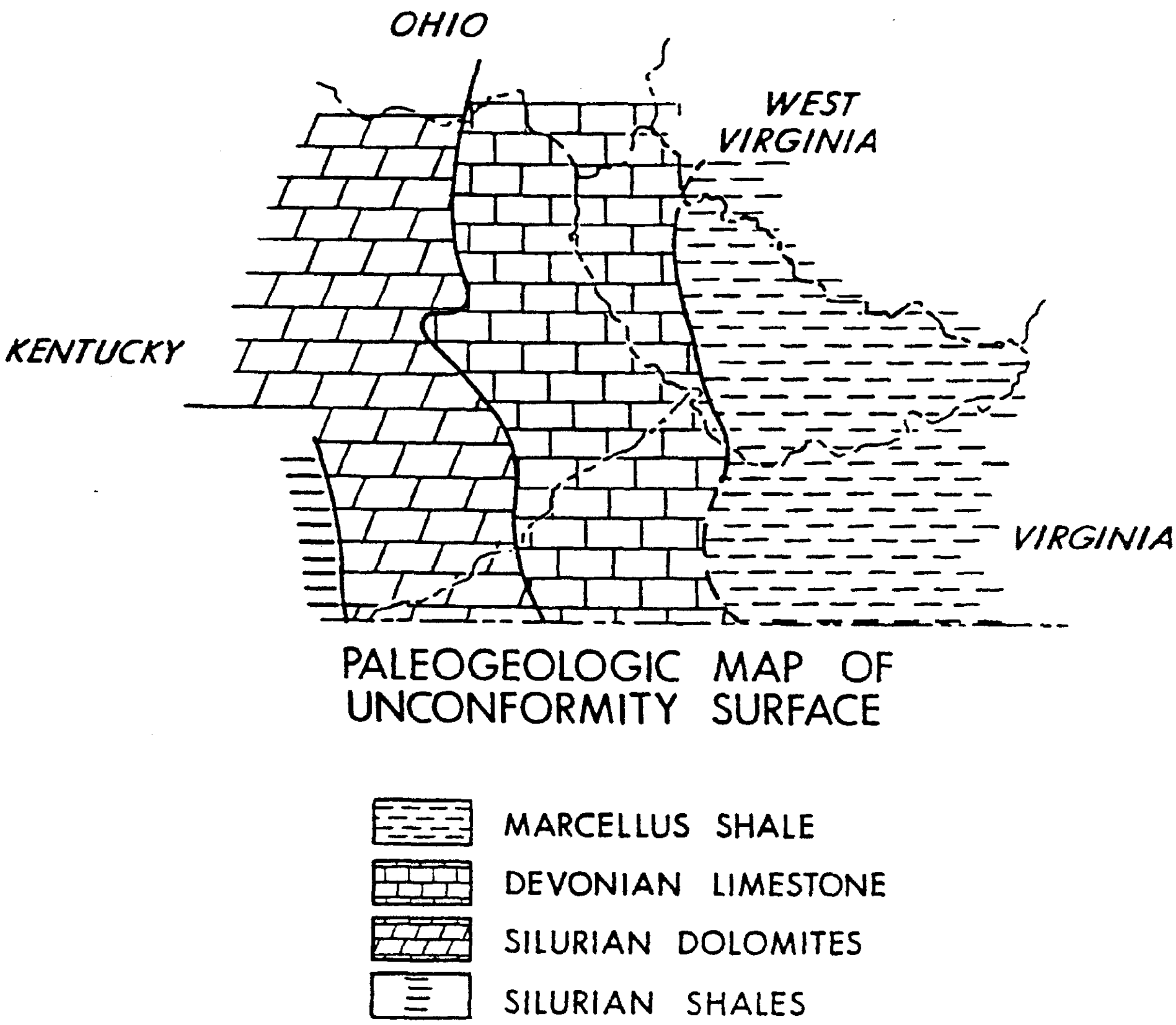

Figure 20. Paleogeologic map of the unconformity surface.

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the west and to the south. As these rocks were being exposed and weathered, supplying very fine-grained clastics into the basin, a similar influx of clastics from the eastern side of the basin eventually in-filled the depositional basin.

Progressive onlap to the west resulted in the deposition of sediments in a rather narrow restricted basin which terminated in the southern part of what is now West Virginia (Figure 21). Figure 21a shows the limit of the basin in Geneseo time which, by West River time (Figure 21b), was well established southeast of the Warfield Anticline. During Sonyea time (Figures 21c, 21d) the basin expanded from a position east of the Warfield Anticline to the approximate position of the western edge of the Rome Trough. The edge of the basin shifted to the west during West Falls time beyond the limits of the study area and a shelf developed on the previously exposed surface. Figure 22 is a diagramatic sketch of the inferred depositional surface in southern West Virginia during the Middle and Late Devonian. Figure 22A represents Sonyea time when the shallow shelf that had developed on the western side of the basin was the site of relatively slow deposition with a uniformly thin sequence of sediments being deposited. Beyond the edge of this shelf there was a rapid thickening eastward due in part to the long and narrow configuration of the basin and subsidence along its axis. It was in this part of the basin that the turbidite siltstones (Figures 17 and 18) were deposited. This relatively narrow basin existed through late Sonyea time with only minor modification, after which a major onlap developed to the west. With this transgression, the flat land surface between the old strandline

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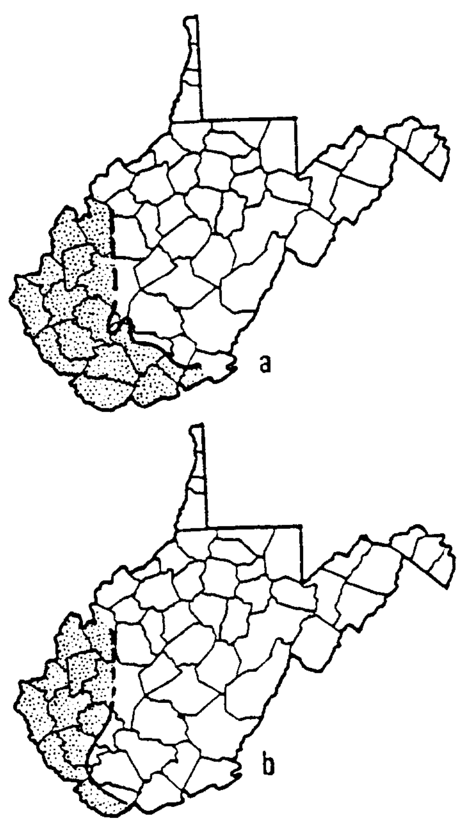

Figure 21. Southern limits of depositional basin in Genesee and Sonyea time. a. Geneseo time, b. West River time, c. Middlesex time, d. Cashaqua time. Land area is stippled.

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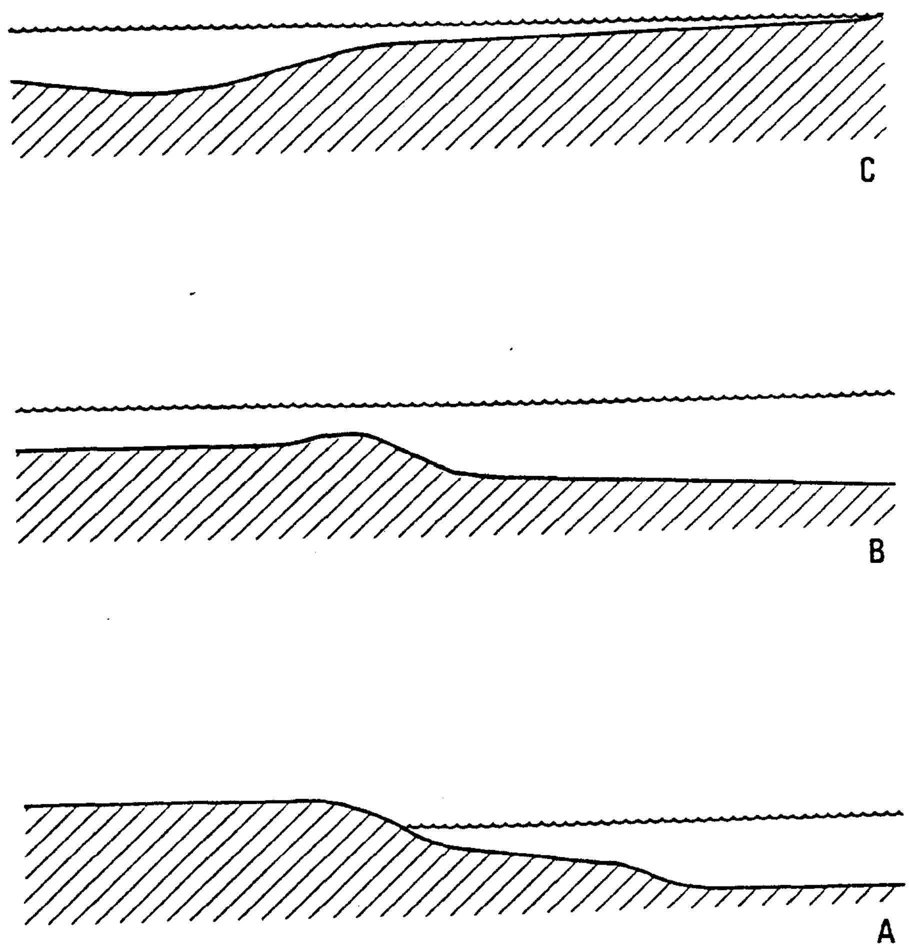

Figure 22. Diagramatic sketch of the inferred depositional surface during the Late Devonian. A. Sonyea time, B. West Falls time, C. latest Devonian time. Vertical scale greatly exaggerated.

and the new West Falls strandline (west of the study area) became the new shelf (Figure 22B). This shelf, with a ridge along the edge, became the site of deposition of the black shale of the West Falls Formation and the Ohio Shale. Evidence for the ridge is a slight thinning of the stratigraphic section in this location during West Falls time that became more pronounced during Huron time and is visible on the isopach map of the Huron Member (Plate 6). Figure 22C represents the basin topography in latest Devonian time when a very broad eastern shelf had developed flanking a narrow basin in the western part of the study area. The apparent reversal of dip results from the progradation of the eastern shoreline and the infilling of the basin.

A concern of most studies dealing with the Middle and Upper Devonian clastic sequence in the western and southern parts of the Appalachian basin is the origin of the black shale found within the sequence. Black shale can derive its color from disseminated organic detritus variously combined with finely divided pyrite, metalic oxides, or other dark minerals. The preservation of great amounts of organic matter requires a highly reducing, oxygen-free environment. The depth of water in which these conditions can be found in modern environments ranges from extremely shallow to extremely deep; thus, there are a multitude of environments in which black shale can form.

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The presence of black shale on the unconformity surface, the "perfection of lamination", the onlapping of the unconformity by progressively younger black shale beds which overlap older black shale beds, and the preponderance of rocks deposited in shallow water environments during the Lower Paleozoic in the eastern interior of the

United States, are some of the arguments used by Conant and Swanson (1961) to suggest a shallow water environment for the Upper Devonian clastics. I concur with this interpretation for several reasons. I believe the erosional surface was subaerially exposed during the Late Devonian, subsequently transgressed by the sea and, while the sea was still very shallow, the black shale began to be deposited. It seems illogical to expect a "deep water" black shale to have been deposited directly above a subaerially exposed erosional surface. Also, the shale is generally distinctly laminated with discontinuous lenses of silt-size quartz dispersed throughout. One may ask, "Why are there no sedimentary structures found in the black shale truly indicative of a shallow water environment such as current ripples, flaser bedding, and large-scale cross stratification?" Perhaps, due to the nature of the sediments, these structures were not preserved, or, perhaps, the currents were strong enough to form indicative sequences of sedimentary structures but for some reason the sediments at the sediment-water interface were not free to respond to the currents.

Much of the organic detritus in the Devonian black shale is of marine plant origin. The great amount of algal "spores" present in the rock identified as Tasmanites (Boneham, 1977), the identification of the fossil alga Protosalvinia by Schwietering and Neal (1977), and the palynological studies reported by Zielinski and others (1978), suggest that the predominant plant variety in the Devonian sea was of algal affinity. The presence of algae in great abundance, both as floating algal accumulations and as sediment-binding algal mats, can mask the true hydrodynamics of an environment. Neumann and Scoffin

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(1970) reported that subtidal mats off the Bahamas could withstand direct current velocities three to nine times higher than the maximum tidal currents recorded in the mat environment. They also found that mat-bound sediments could withstand direct current velocities two to five times greater than those necessary to move the same sediment devoid of organic matter. The energy of the environment was in no way reflected in the sediments at or below the sediment-water interface. I suggest, therefore, that an analogous situation existed in the Upper Devonian where algal bound sediments in a shallow water environment likewise masked the effects of the true energy of the environment. Unlike algal carbonates where plant structures are preserved, the algal bound muds retain only a laminated texture like that seen in the black Devonian shale. Also, silt-size quartz appears to be coarser in the black shale than in the non-black shale (R.J. Vinopal, personal communication). An algal bound sediment may well include grains of coarser material which were trapped rather than transported to other parts of the basin. Lineback (1970) suggested the existance of a floating algal mat as the source of the organic matter in the black shale of the New Albany Shale of Indiana.

The vast amount of organic material present in the Devonian black shale might have produced a very toxic reducing environment essentially devoid of benthic invertebrate organisms. Pelagic organisms, however, are found and include cephalopods, planktonic ostracods, and the conodont bearing organism. This would account for the paucity of invertebrate remains in the black shale. It also would account for the great quantity of dispersed pyrite found concentrated in the black shale.

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The decaying organic matter would produce a reducing environment where sulfate-reducing bacteria could develop and thus preserve a great amount of organic matter and produce pyrite. The controlling factor, therefore, in the accumulation of the black shale, seems to have been the presence of great quantities of organic matter, most likely of algal affinity.

The Devonian clastic sequence has a pronounced cyclic nature. Each cycle, as described earlier, has a basal black shale overlain by gray shale and siltstone. Schwietering (1979) suggests that these cycles resulted from periodic shifts in the black shale facies as a result of orogenic pulses. This model, however, does not explain the sudden changes demonstrated between cycles, or the apparent non-association of black shale between cycles. The contact between the basal black shale of a cycle and the underlying non-black shale or siltstone is sharp. If, as suggested by Schwietering, a rise in sea level is associated with orogenic pulses which in turn would result in the deposition of non-black sediments, there would be a gradation between a basal non-black shale and an overlying black shale rather than a sharp contact. I suggest that the orogenic pulses caused a shallowing of the water and because of the abundance of organic matter (plants) there was a stagnation of the environment which in turn, as explained previously, allowed the preservation of the black muds.

An alternative explanation for the cyclic nature of the Devonian onlap clastics is the possibility of indirect control over deposition by rock types exposed in the eroding surface. A gross correlation between the principal rock type exposed below the unconformity and the

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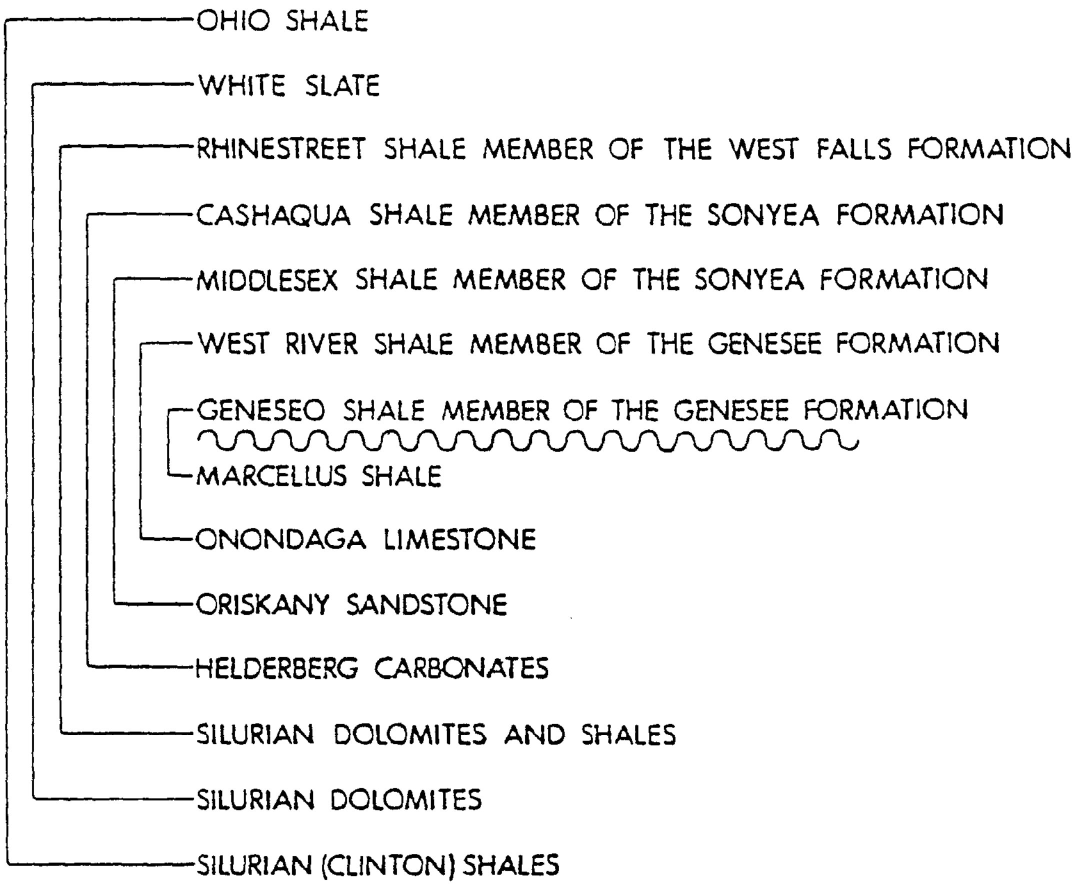

Figure 23. Relation of sub-unconformity lithologies to rocks deposited in the basin.

onlap sequence is given in Figure 23. It appears that as the sea transgressed a terrigenous clastic interval, an onlapping black shale would develop and as the sea moved past a carbonate interval, an onlapping gray shale developed. There is a gross correlation between the thickness of the units above and below the unconformity with the color of the onlapping sequence resulting primarily from the amount of contained organic matter. It is suggested, therefore, that the exposed rock type beneath the unconformity affected in a subtle way the physical/chemical character of the water in which the marine plants were living, enough to control whether or not the plants would flourish. This may explain the large-scale cycles in the Upper Devonian. The small-scale cycles within the gray shale sequences may be explained in terms of either large-scale algal blooms similar to the red tides which produce a great amount of organic material and a toxic, reducing environment or, most likely, they may represent black shale deposited in depressions on the sea floor where circulation would have been restricted thus preserving the shale.

The major elements of the geologic history and development of the southern Appalachian basin in the Upper Devonian are depicted in Figure 24. These schematic diagrams illustrate the position of the mountains, the shoreline, and the major depositional platform for three successive intervals within the Upper Devonian. Time A approximates the beginning of Sonyea time when the basin was narrow and the eastern highland was poorly developed in the south. Figure 22A illustrates the inferred depositional surface corresponding to this time. Time B represents late West Falls time when the sea had transgressed a considerable

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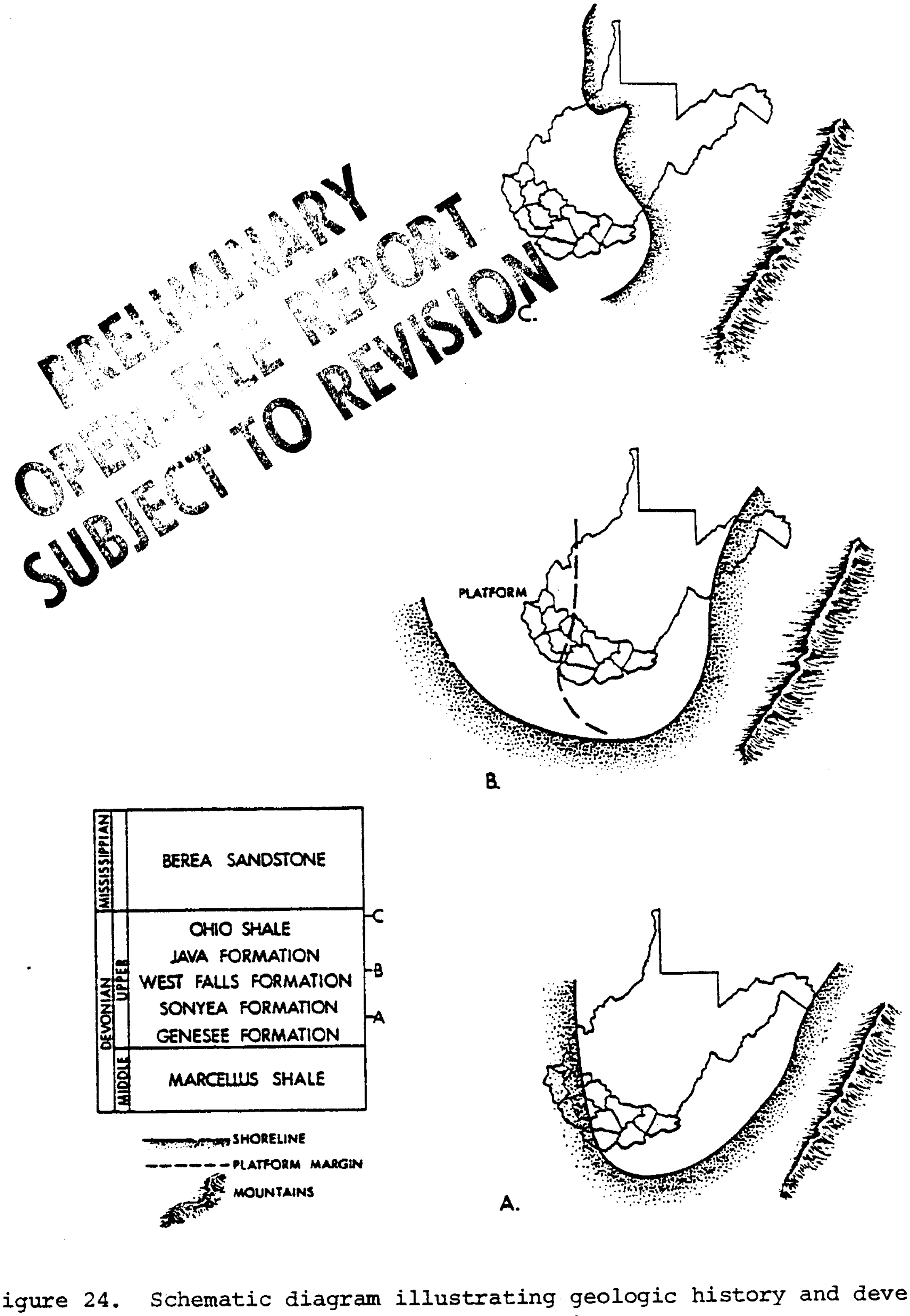

Figure 24. Schematic diagram illustrating geologic history and development of the southern Appalachian basin.

distance to the west and the old strandline had become the edge of the shelf-like platform (see Figure 22B). The southern part of the eastern highland had developed beyond that illustrated in Time A. The shoreline had prograded westward in the north and the sea had moved southward. Time C represents latest Devonian time when the eastern mountains provided abundant sediments to the Catskill delta to the north, and to the incipient Virginia-Carolina delta to the south.

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DEVONIAN SHALE GAS

Most hydrocarbons are thought to originate in a source rock, migrate, and accumulate in a porous rock body of completely different properties. The Devonian black shale of the Appalachian basin is a peculiar rock unit because it acts as both the source for the natural gas as well as the reservoir for its accumulation.

THE SOURCE

The source for most hydrocarbon is rock rich in organic matter, especially the insoluble variety known as kerogen. Hydrocarbon is generated when kerogen, a highly complex organic molecule, undergoes decomposition due to increased temperature and pressure during burial and diagenesis. The production of hydrocarbon depends not only on the burial history of the rocks but also on the type of kerogen found in the rocks.

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Three types of kerogen have been identified based on their position on the van Krevelen (H/C, O/C) diagram (Tissot and Welte, 1978) (Figure 25). Type I kerogen has a high H/C ratio and low O/C ratio. The origin of this type of kerogen is most likely algal remains or extensively transported organic matter. Type II kerogen has a moderately high H/C ratio and low O/C ratio and is derived from marine sediments containing planktonic organisms. Type III kerogen has a low H/C ratio and a high O/C ratio suggesting an origin from organic matter derived from terrestrial plants.

The production of hydrocarbon from kerogen involves three stages of transformation; diagenesis, catagenesis, and metagenesis. Diagenetic

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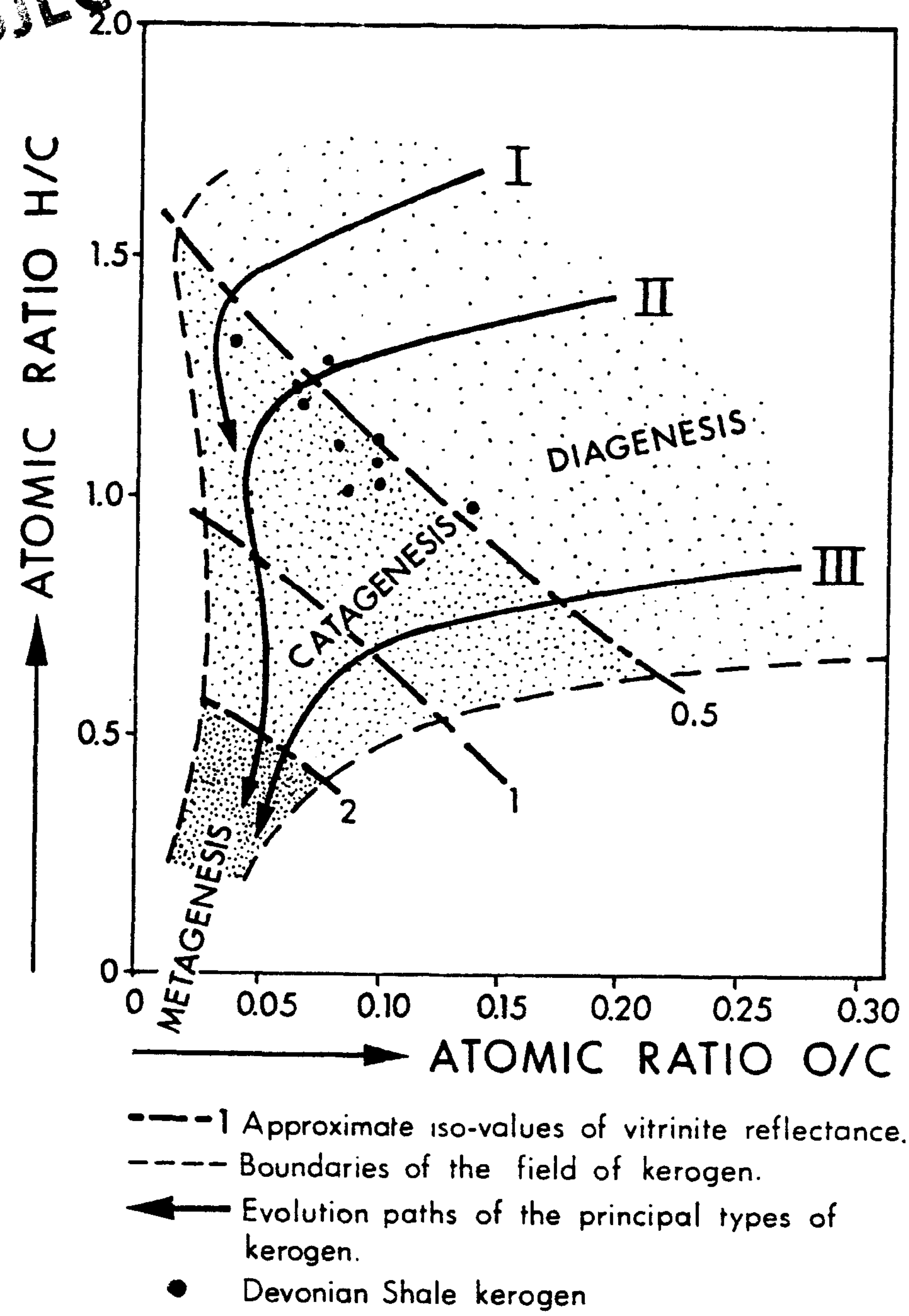

Figure 25. van Krevelen diagram showing maturation level of Devonian shale kerogen. (diagram after Tissot and Welte, 1978; data from Zielinski and others, 1977).

changes in kerogen show a decrease in oxygen content and a complimentary increase in carbon content. This stage also can be characterized by a vitrinite reflectance of 0.5% or less. Very little hydrocarbon is generated in this stage, mainly dry methane, water, and carbon dioxide. The diagenetic stage gives way to the thermogenic stage of catagenesis. With catagenesis there is a decrease in the hydrogen content and the beginning of the "cracking" process. This phase is characterized by a vitrinite reflectance of 0.5 to 2.0%. This is the main zone of oil generation and the beginning of "wet gas" generation. Continued increases in temperature lead to metagenesis where alteration of the original kerogen structure produces the "dry gas" zone. This stage is characterized by vitrinite reflectances in excess of 2.0%.

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The elemental composition of kerogen in the Devonian black shale is represented on the van Krevelen diagram of Figure 25. The data are for the shale interval in a core from Martin County, Kentucky, as presented in a paper by Zielinsli, Attalla, Stacy, Craft, and Wise (1978). Most of the kerogen is of the Type II variety or transitional between Types II and III. This would indicate a quantity of terrestrially derived plant matter. This is in agreement with the findings of Zielinski, Nance, Seabugh, and Larson (1978) based on palynological studies.

Ting (1977) reported a mean maximum reflectance of dispersed vitrinite ranging from 0.56 to 0.78% with an average of 0.68% for samples of the shale taken from the Lincoln County, West Virginia, core (Lincoln 1637). The distribution of samples and their reflectance is given in Figure 26. The reflectances of the vitrinite derived from

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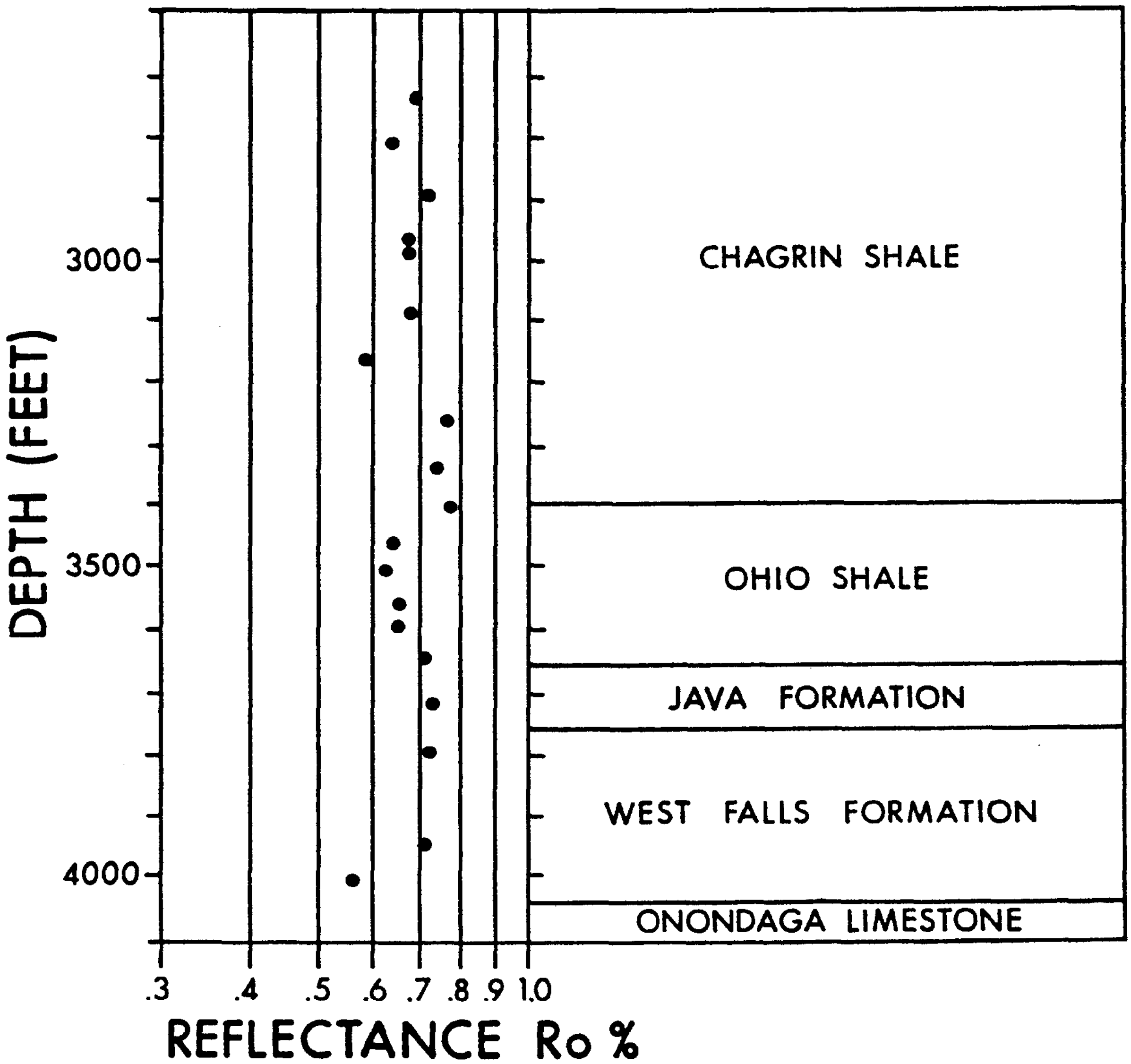

Figure 26. Reflectance of dispersed vitrinite in a Devonian shale core (after Ting, 1977).

the black shale is slightly less than that derived from the gray shale. This may indicate differences in the diagenetic changes in the black shale relative to the gray shale and siltstone or it may indicate a different source for the plant matter found in the black shale.

The elemental composition of kerogen and the reflectance of dispersed vitrinite both indicate that the shale is in the early catagenic stage of hydrocarbon generation. Figure 27 shows the relationship of the Devonian shale kerogen to the zones of petroleum generation and destruction. Given a mixture of marine and terrestrially derived organic matter, a wet gas should have been generated by thermal cracking. The Devonian shale kerogen, however, has not been subjected to temperatures sufficient for cracking a kerogen suite of mixed origin. As the amorphous portion of the suite has been heated sufficiently for oil generation, it is suggested that this portion of the kerogen is the source of the heavier hydrocarbons found in the shale gas and that as a whole the Devonian shale of the southwestern West Virginia area is a submature source rock.

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GAS COMPOSITION AND PHYSICAL PROPERTIES

The composition of shale gas from West Virginia and the Appalachian basin has been studied for many years. Several papers have been published including those of Price and Headlee (1937, 1938), Headlee (1949), Roth (1968), and natural gas analyses by Moore, Miller, and Shrewsbury (1966). The data of the latter are the primary source for the following discussion.

The average composition of shale gas from southwestern West Virginia,

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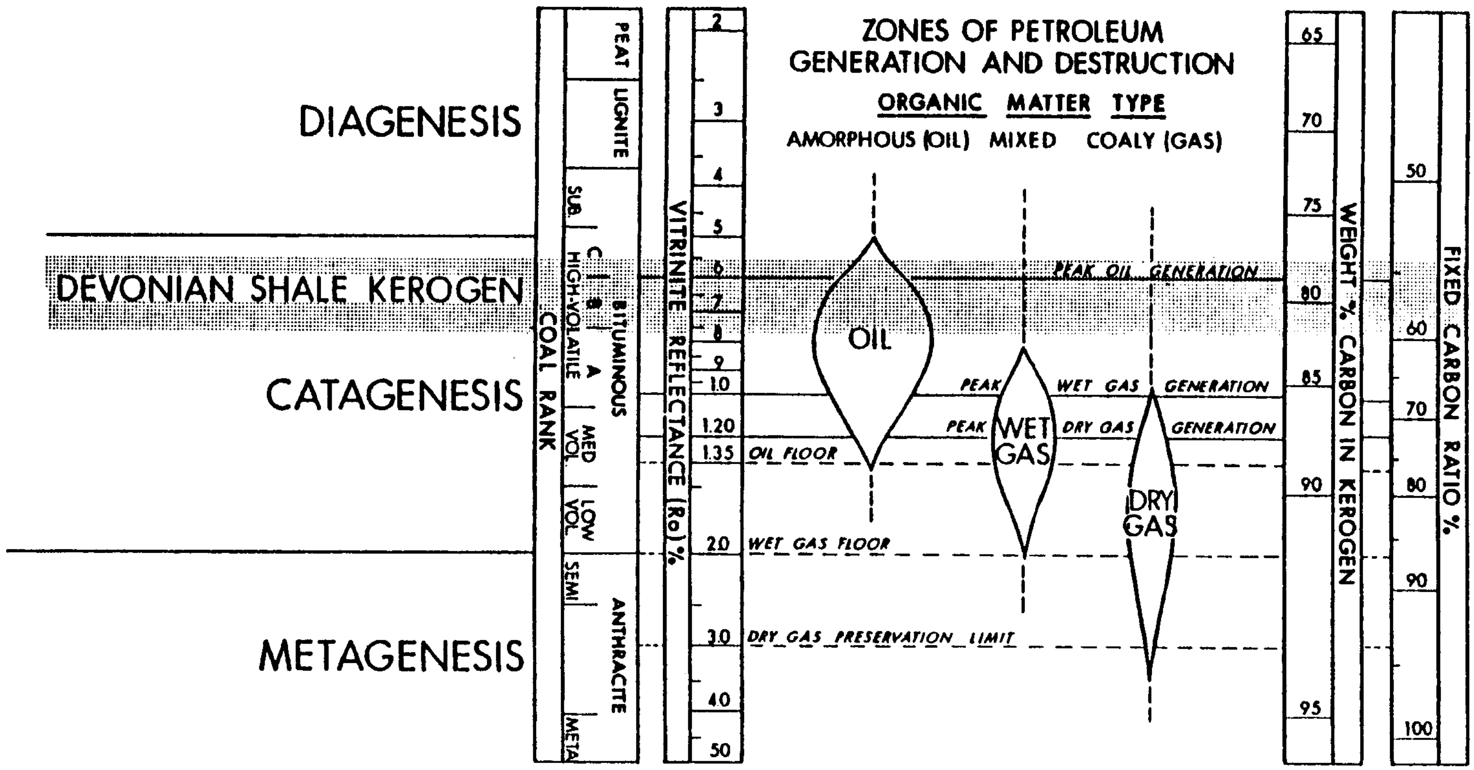

Figure 27. Relation of Devonian shale maturation to zones of petroleum generation and destruction(diagram from Tissot and Welte, 1978).

based on fifteen analyses, is given in Table 1. Shale gas is, for the most part, a non-associated wet gas with an average 18.8% non-methane hydrocarbons and 2.1% inert gases. The distribution of C_1 to C_{1-5} ratios, which is commonly used to characterize the wetness of natural gas, is given in Figure 28. The trend represented is for the ratio to increase from west to east indicating a greater content of methane in the east as would be expected with an increase in depth and thermal maturity.

Related to this trend in hydrocarbon composition is that of the heating value and the specific gravity (Figure 29). With increased relative percentage of methane, there is a decrease in heating value (Btu) approaching that of pure methane. Levorsen (1967) states that commercial gas heating values generally fall within the range of 900 to 1200 Btu per cubic foot. The Btu value of shale gas varies from 1132 to 1309 Btu in the primary producing areas but is as low as 999 Btu in the now inactive Pineville Field of Wyoming County.

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The trend of the specific gravity of the shale gas also decreases toward the east. There may, however, be a slight increase in the area of the Rome Trough, which would be in agreement with the findings of Headlee (1949) who found that the specific gravity of the gas in fields in Kanawha County increased down structure.

The distribution of percentages of the various hydrocarbon species is given in Appendix B. Four trends are noted and include an increase toward the east, an increase toward the west, an increase in the area of the Rome Trough, and no trend. Methane is the only hydrocarbon with the general trend of increasing toward the east. Most of the

Table 1. Summary of Shale Gas Composition

	Mean	Range
Methane	78.9	74.7-82.5
Ethane	12.2	8.6-14.3
Propane	4.8	3.3- 7.5
N-Butane	1.1	0.7- 1.8
Isobutane	0.3	0.2- 0.5
N-Pentane	0.1	0.1- 0.2
Isopentane	0.2	0.1- 0.4
Cyclopentane	Trace	Trace- 0.1
Hexanes +	0.1	0.1- 0.2
Nitrogen	1.9	0.5- 4.3
Oxygen	Trace	0.0- 0.3
Argon	Trace	0.0- Trace
Helium	Trace	Trace- 0.1
Hydrogen	0.1	0.0- 0.2
Hydrogen Sulfide	0.0	0.0
Carbon Dioxide	0.1	0.0- 0.2
Heating Value*	1211	1132- 1309
C_1/C_{1-5}	0.81	0.75- 0.86

Based on analyses by Moore, Miller, and Shrewsbury(1966)

* Calculated gross Btu per cu. ft., dry at 60°F and 30 in. Hg

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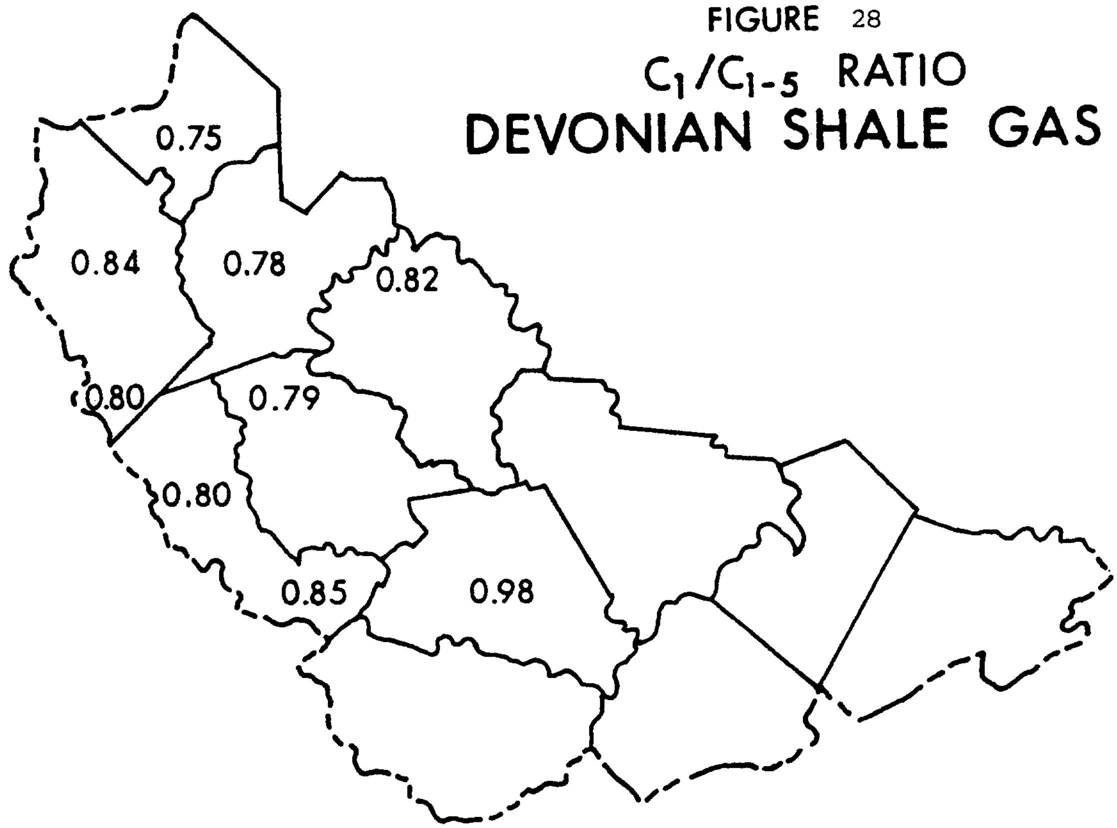
FIGURE 28

C_1/C_{1-5} RATIO

DEVONIAN SHALE GAS



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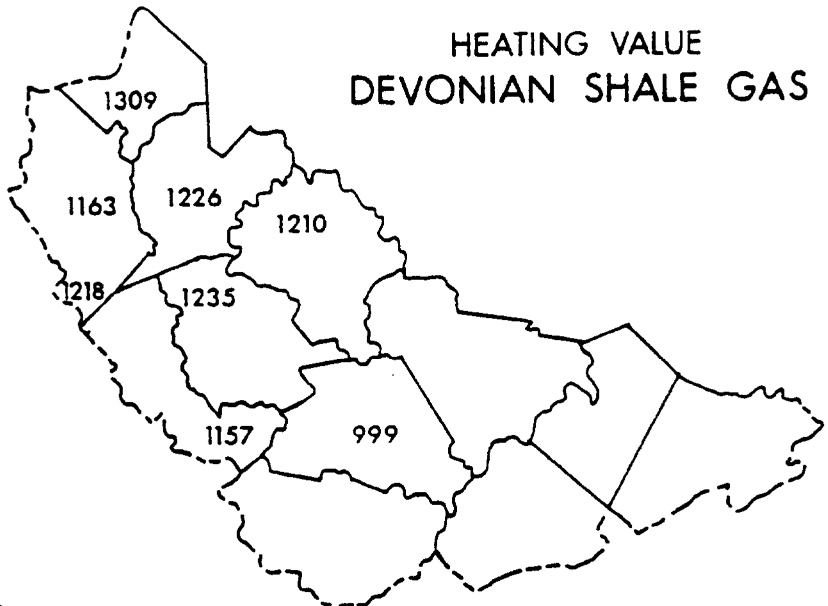

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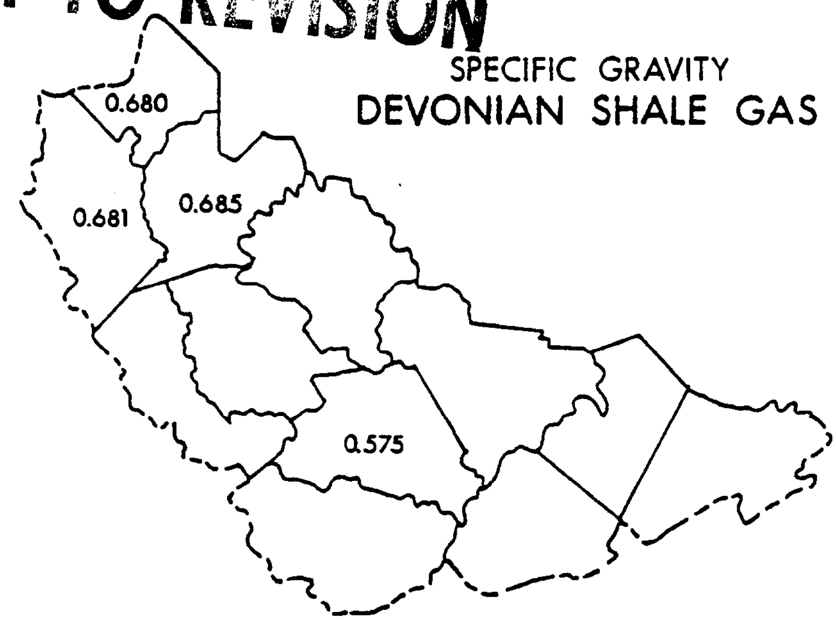

Figure 29. Heating Value and Specific Gravity--Devonian Shale Gas

heavier hydrocarbons compliment the methane trend by increasing toward the west. Among these are ethane, normal butane, iso-pentane, and cyclopentane. Iso-butane and normal pentane and the hexanes plus show no trend.

The distribution of the percentages of the inert gases found in shale gas also is given in Appendix B. The trend of most of the inerts (nitrogen, hydrogen, helium, and argon) shows an increase toward the west-southwest. Oxygen and carbon dioxide, however, show an increased percentage in the area of the Rome Trough. Shale gas is free of hydrogen sulfide, unlike the gas of the Huntersville Chert and Oriskany Sandstone, units stratigraphically below the shale section.

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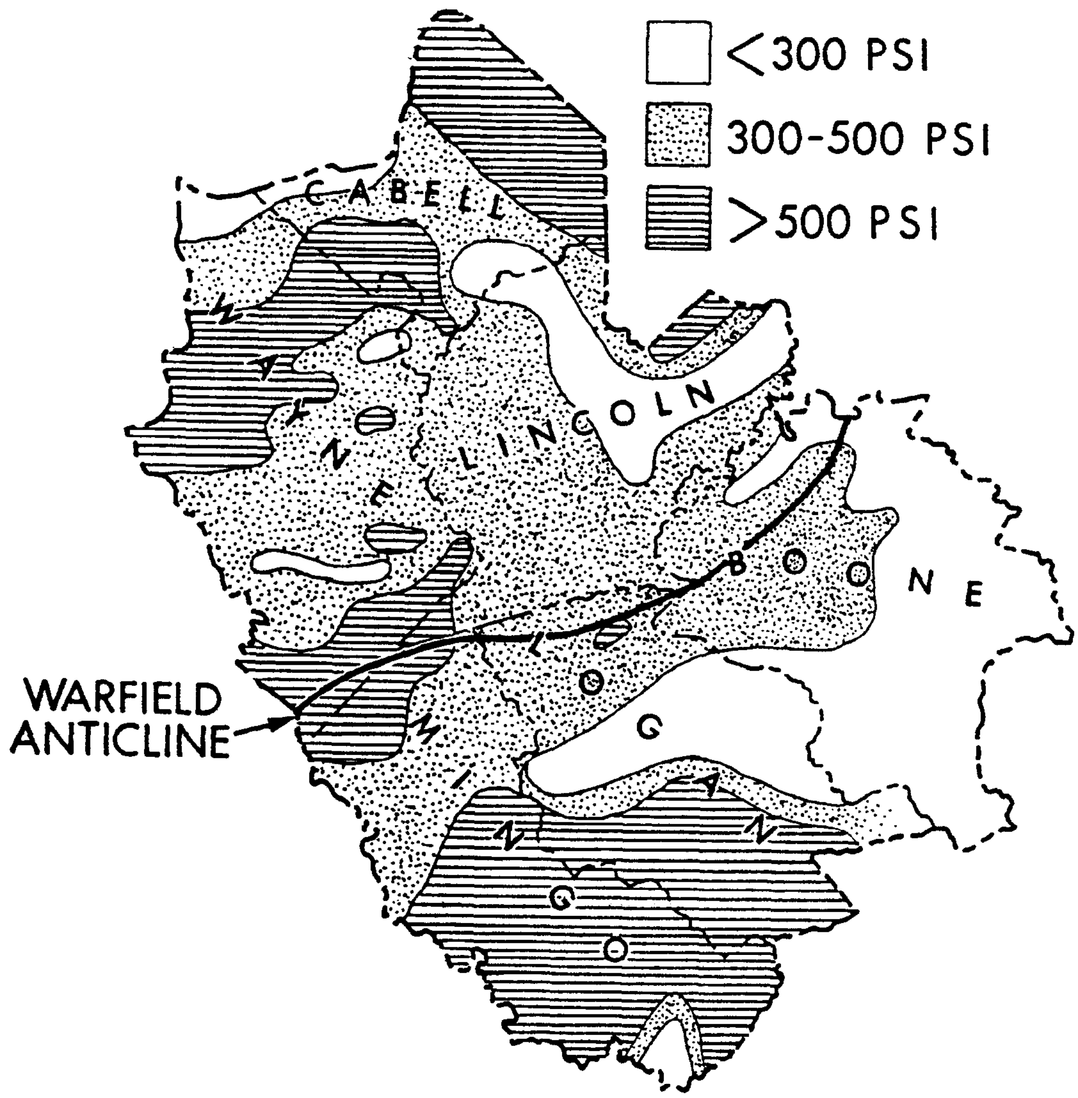
THE RESERVOIR

The characteristics of a single reservoir are varied and complex and no attempt to characterize the reservoirs of the Devonian shale gas fields will be made; however, a few parameters will be discussed. Rock pressure or reservoir field pressure (Figure 30) is controlled by the extent to which fields are developed and by structure in the producing area. In the Devonian shale fields, areas with greater than 300 psi are best developed west of the Warfield Anticline in Boone and Logan Counties. High pressure areas in Wayne County and along the Wayne-Mingo County boundary are associated with anticlinal structures. The high pressure areas of southern Mingo County and northern Cabell County show no relation to local structure and may not truly represent the pressures of these areas. This may result from either a paucity of data points in the areas or data representative of non-

Figure 30

ROCK PRESSURE



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Devonian shale producing intervals. There are too many factors which affect the quality of the pressure data, namely the lack of data and differences in measuring pressures in older and newer wells, to make specific interpretations with confidence; however, some general trends can be seen. First, high pressure areas can in part be explained by local structural features. Pressures tend to be higher along the crests of minor anticlines and lower along the flanks. Second, pressures in the main producing areas of Lincoln, Wayne, and Mingo Counties not directly associated with local flexures are higher than in non-producing areas. These trends would suggest an overall interconnection of what were presumed to be discrete reservoirs.

Porosity in the Devonian shale is very low. Generally averaging less than 3%, the absolute porosity of the shale in Lincoln County core well 1637 was found to be 1.98% (W.V.G.E.S., 1978). A summary of the mean porosity for each of the major stratigraphic units of the core is given in Table 2. Permeability, likewise, is almost negligible. Smith (1978) reports a permeability for the shale of generally .005 md or less and Kalyoncu and others (1978) report permeabilities on the order of .007 md. In either case, the permeability of the rock is almost non-existant.

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Considering these porosity and permeability data, it is difficult to explain shale production at all. There must be some other factor which controls the accumulation of the gas and that, most likely, is the existance of a system of interconnecting fractures. This conclusion is not new and arguments both in favor and in opposition have been presented for many years. Lafferty (1935) and Billingsley and

Table 2. Mean Porosity for Stratigraphic Intervals in a Core from Lincoln County(Lincoln 1637)

Chagrin Shale	1.34 %
Huron Member of Ohio Shale	
upper part	1.32
lower part	2.41
Java Formation	1.87
Angola Shale Member of West Falls Formation	2.84
Rhinestreet Shale Member of West Falls Formation	2.78
Grand Mean	1.98

Data from West Virginia Geological and Economic Survey(1978)

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Ziebold (1935) postulated a fractured reservoir and later Hunter and Young (1953) also recognized the importance of fractures in Devonian shale gas production. Bagnall and Ryan (1976) explained production decline curves (Figure 31) for shale wells in southern West Virginia in terms of a fractured reservoir where the best wells (those with highest initial flows) intersect more fractures than wells with lower initial flows. The steepest part of the decline curve represents "free gas" found in open fractures. The next section of the curve, between the near-vertical part and the horizontal part, represents free gas and gas adsorbed on the sides of the fractures. The horizontal part of the curve represents adsorbed gas which changes phase to free gas and bleeds off slowly from the matrix of the shale. Wells intersecting the greatest number of fractures will thus produce a greater volume of "free gas" and provide more pathways for matrix gas to reach the borehole. Consistent large-scale fracture systems within the shale section can be seen in outcrop from New York to Kentucky. It is not surprising, then, that these fracture sets are intersected in the subsurface. In fact, mineral-filled, unfilled, and slickensided fractures are found in the Devonian shale. An average of seven fractures per one hundred feet of core was reported by the West Virginia Geological and Economic Survey (1978) for a cored well in Lincoln County, West Virginia. Arguments presented in the Survey report favoring matrix porosity over fracture porosity as the more significant type are not considered valid in light of the negligible porosities and permeabilities described for the matrix. Considering the statement of Gorham and others (1979) that "a single fracture of

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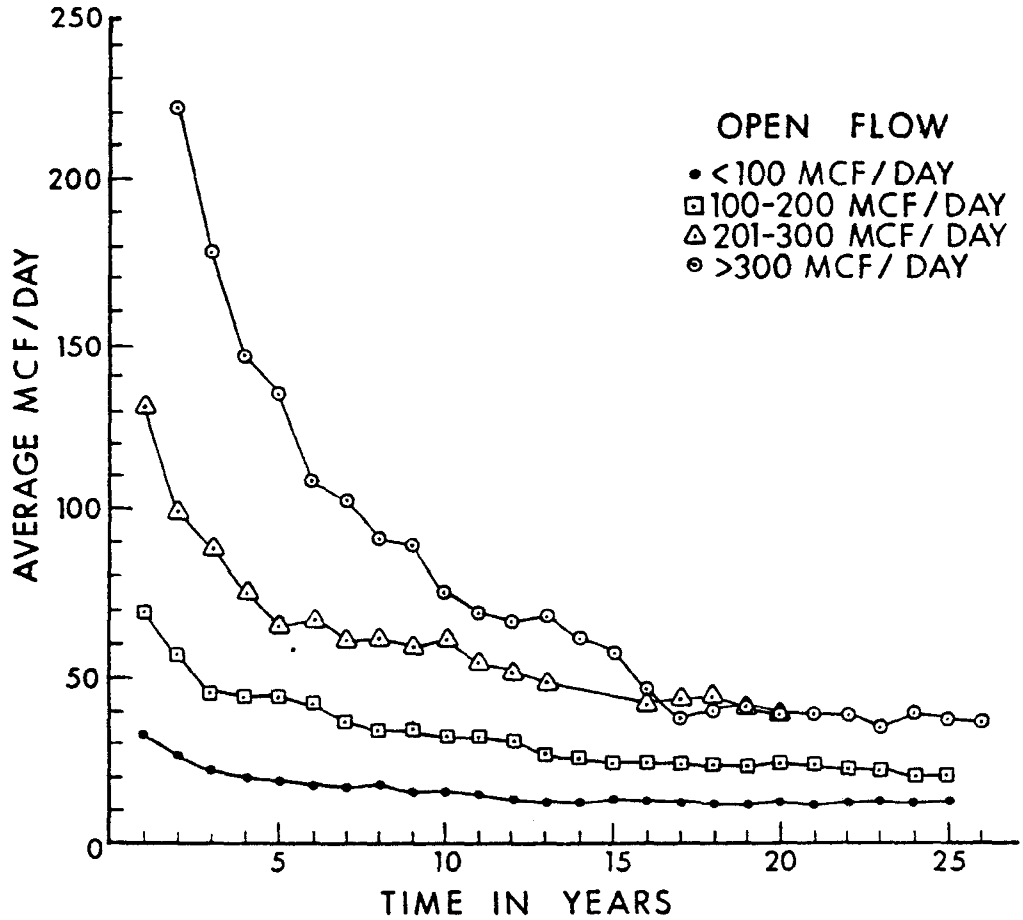

Figure 31. Averaged decline curves for Devonian shale gas production in southern West Virginia (after Bagnall and Ryan, 1976).

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1/25 in. (1 mm) wide crossing a well bore in an oil reservoir can provide permeability sufficient to produce between 7,000 and 10,000 bbl of oil per day," it is very realistic then to credit a major part of the gas production in the Devonian shale to the existance of a fractured reservoir.

PRODUCTION CHARACTERISTICS

Devonian shale gas wells are characteristically low-volume, long-lived wells. Initial open flows are typically very low, and wells must be stimulated in some manner in order to produce any volume of gas. For example, two cored wells in Lincoln County show this characteristic very well. The first (Lincoln 1687) has an initial open flow of 95 Mcfd from the Huron Member of the Ohio Shale and a final open flow (after stimulation) of 200 Mcfd. Similarly, in the same well the Rhinestreet Shale Member of the West Falls Formation had only a show of gas before stimulation and 110 Mcfd after. The second well (Lincoln 1636) reported only shows for both intervals, but reported flows of 111 Mcfd and 110 Mcfd for the Huron and Rhinestreet intervals, respectively, after stimulation. Enhanced flow is not always the case and sometimes the stimulation procedure reduces permeability in what would have been a suitable naturally producing well. Figure 32 shows the trend of initial potential of wells across the southwestern part of the state. Initial potential as used here is essentially final open flow of stimulated wells and those wells which produce naturally. The trend is for the greatest potential to be along the flanks of the major structural flexures

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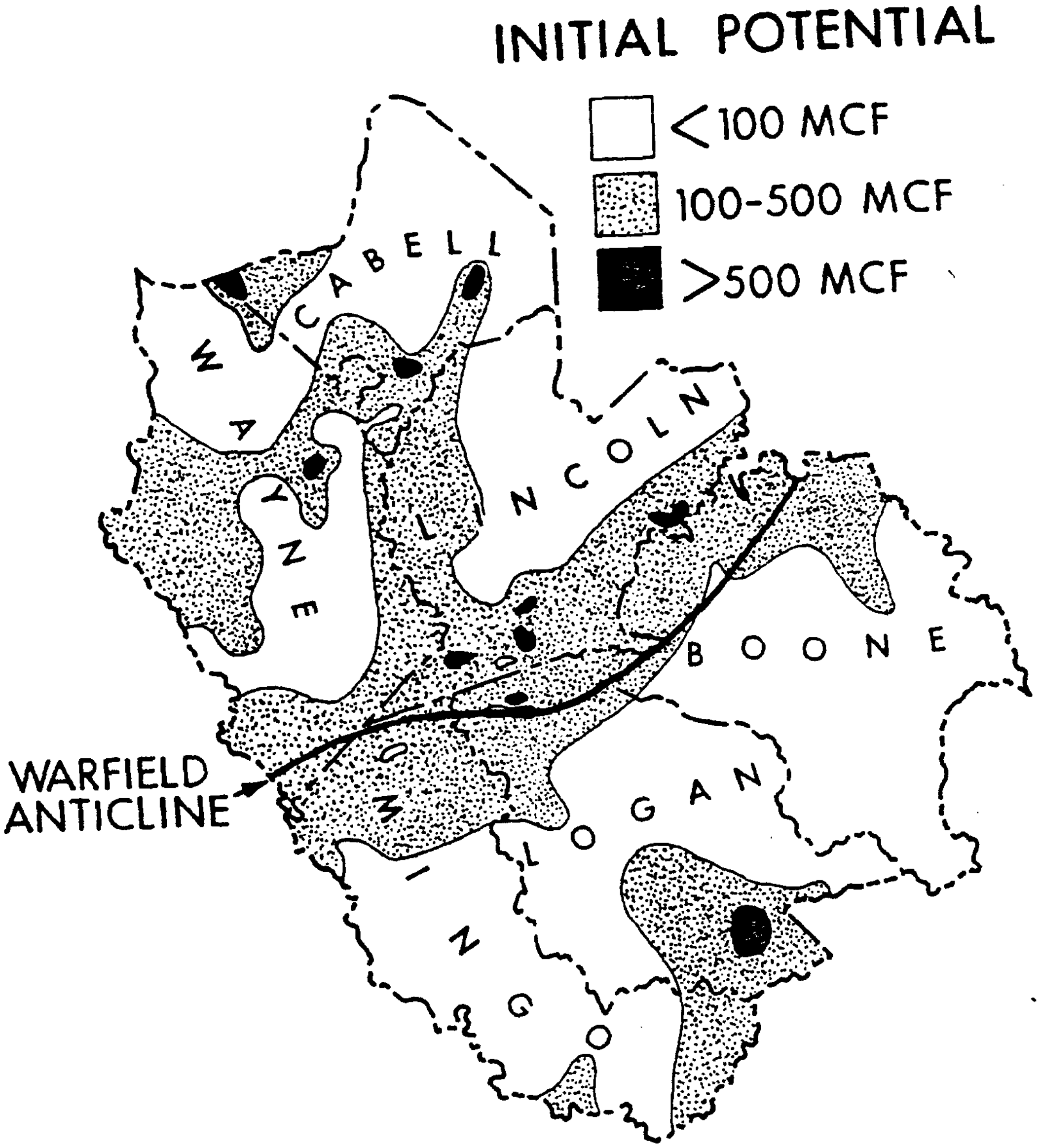
Figure 32



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(Plate 11) in the area. Specifically, the highest potential is along the western flank of the Warfield Anticline in Boone, Logan, and Mingo Counties. This flexure is broad in relation to the fold in Cabell and Wayne Counties where the greatest production is along the crest of the flexure. The apparent high production area of southern Logan and Mingo Counties is based on very few data points and is not considered valid as far as the overall trend is concerned. The relation of potential production to structure can also be seen on Plate 12. Structure on top of the Onondaga Limestone is shown with the location of wells which reported shows in the lower dark shale interval, primarily the Rhinestreet Shale Member of the West Falls Formation in the western part of the study area and in the eastern part of the map area the dark shales of the Sonyea Formation, the Genesee Formation, and the Marcellus Shale. There appears to be a relation similar to that described for initial potentials; shows are located along the western flank of the Warfield Anticline and along the crest of the folds in Cabell and Wayne Counties. There is an area of active gas production from this interval in southern Lincoln County.

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Bagnall and Ryan (1976) reported averaged production decline curves for Devonian shale wells in Lincoln, Mingo, and Wayne Counties (Figure 31). Four curves were generated for each of four open flow intervals covering a period of 25 years showing, predictably, the greater the initial open flow, the greater the average daily production over the life of the well. However, after about fifteen years each curve tends to flatten with the greatest production averaging approximately 40 Mcfd for a well with an initial open flow in excess of 300 Mcfd. Smith (1978) found a linear relationship between cumulative production and initial open flows (Figure 33) for wells fractured with explosives. Twenty year cumulative production ranged from 50 to 900 MMcf with an estimated resource of 200 to 1000 trillion cubic feet (Tcf) of gas in the Devonian shale in the Appalachian basin.

RELATION OF PRODUCTION TO STRATIGRAPHY

Gas production from the Devonian shale in the study area has been primarily from the Huron Member of the Ohio Shale with the lower part of the unit the primary source of the gas (Figure 34). Thin intervals of gray shale which can often be traced for great distances are intercalated with the black shale. Gas shows are often noted immediately below these gray shale units which suggests that these shales may form a barrier to the vertical migration of gas within the interval.

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Most shale wells are drilled just through the Huron Shale interval. In wells drilled through the entire Devonian shale interval to test the Oriskany or Huntersville, a second gas producing black shale interval is often found (Figure 35) which consists of the Rhinestreet Shale Member of the West Falls Formation and older units. Shows are recorded most often from two parts of this interval; the lower part which corresponds with the older units, and at the upper boundary which is due most likely to the interbedding of black shale of the Rhinestreet Shale and the overlying gray shale of the Angola Shale.

Gas shows and intervals with commercial production also can be found in the silty shale and shaly siltstone sequence above the Huron

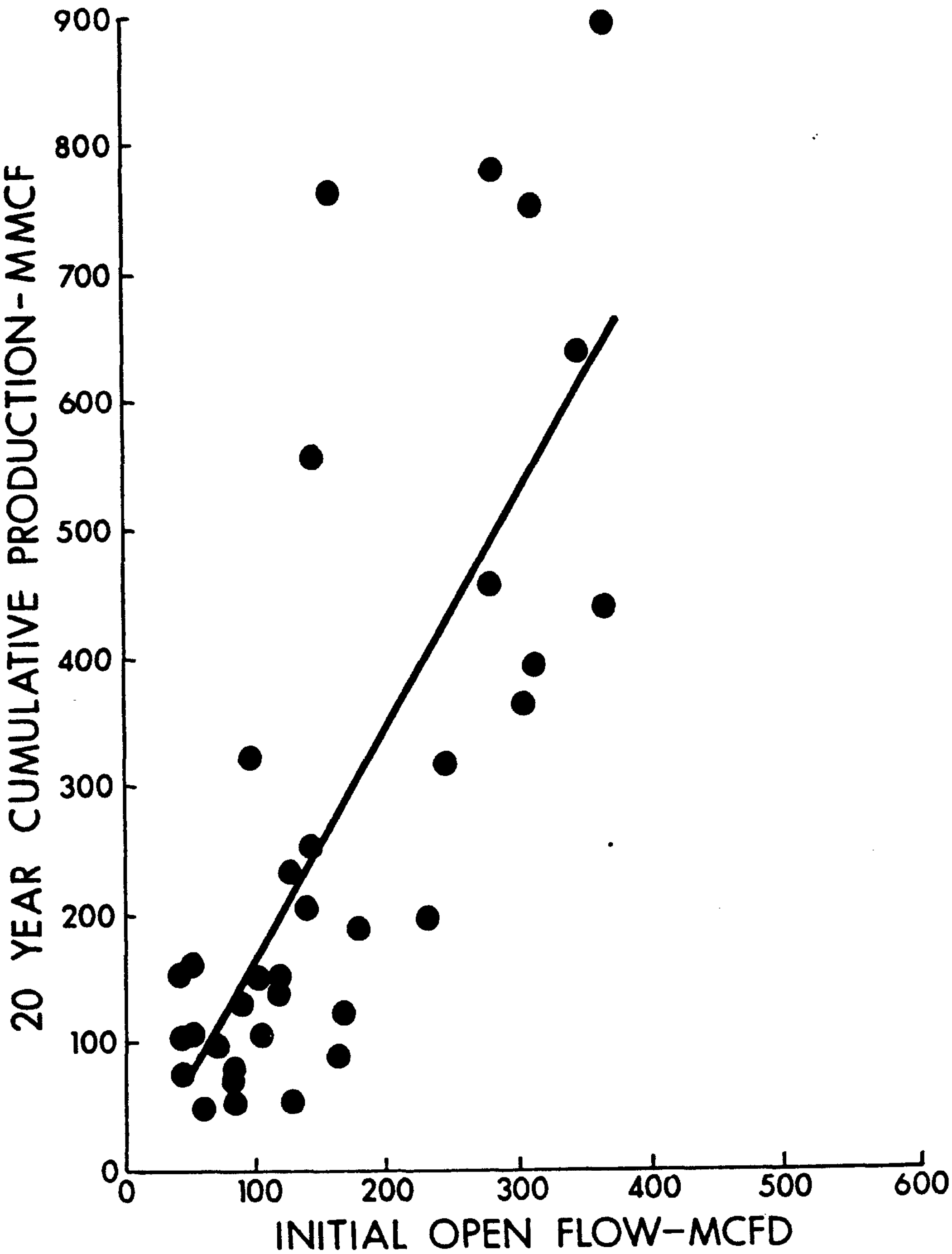

Figure 33. Relation of 20 year cumulative production to initial open flows in southern West Virginia(after Smith, 1978).

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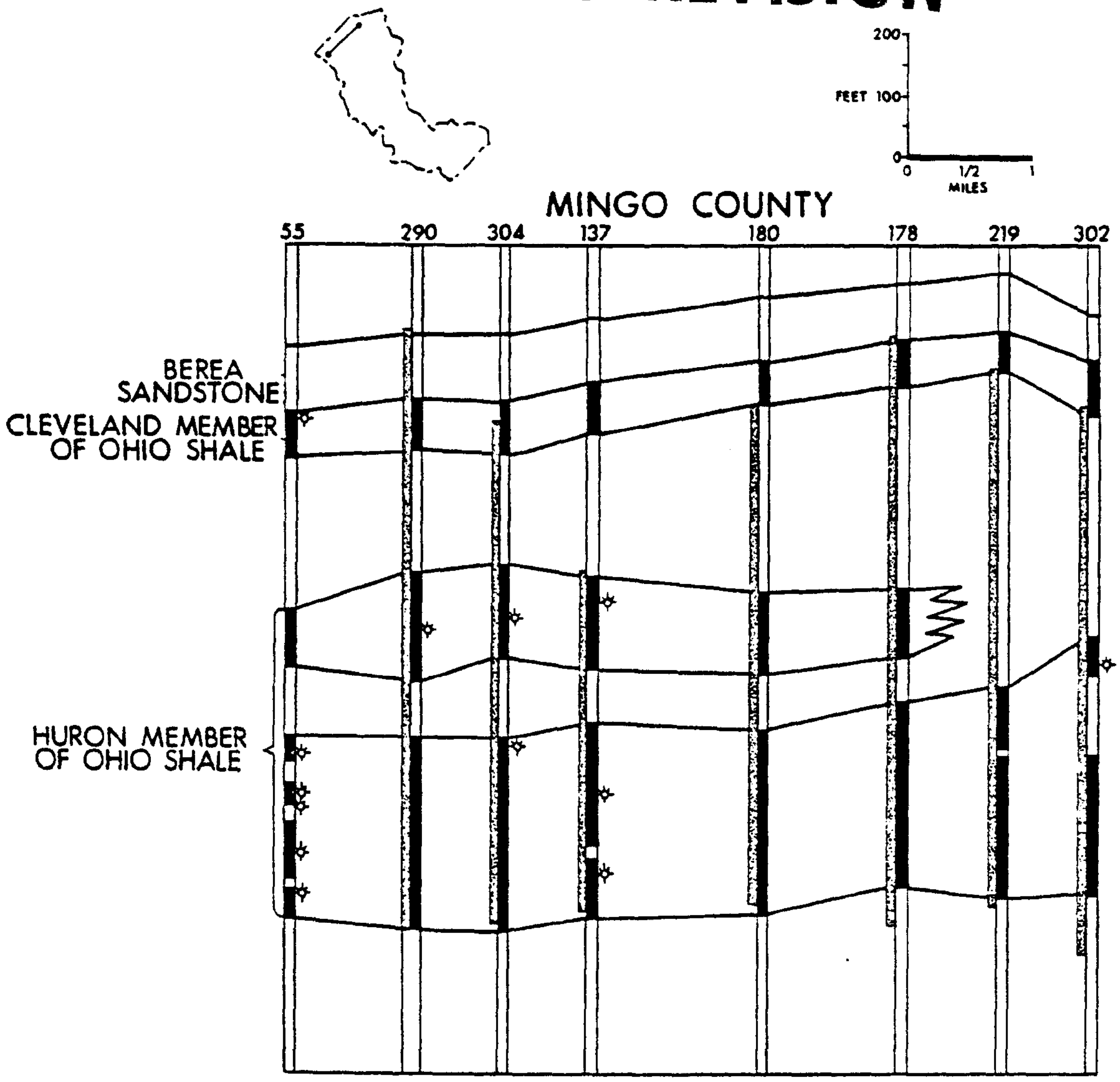

Figure 34. Relation of production to stratigraphy--Mingo County. Black shale intervals indicated by solid black, shot interval indicated by stippled interval.

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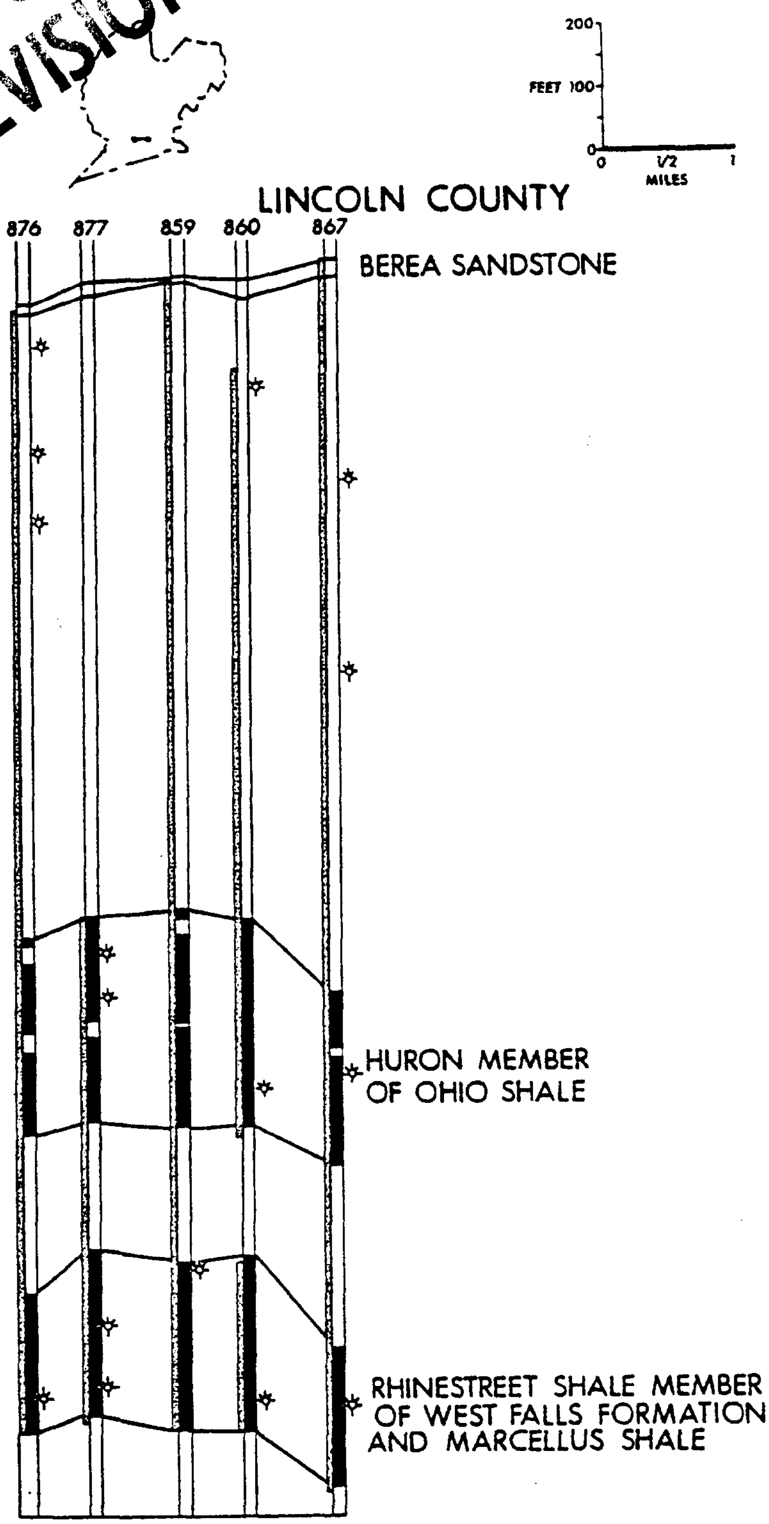

Figure 35. Relation of production to stratigraphy--Lincoln, County. Black shales indicated by solid interval, shot interval indicated by stippled pattern.

Member (Figure 36). Similar intervals are the primary producers in northern West Virginia. Thus far, in the southern part of the state, these units have not produced great quantities of gas.

RECENT PRODUCTION

Haught (1959) reported that about 400,000 acres were known to be producing from the Devonian shale. Cardwell (1977) reported proved reserves in excess of 500,000 acres for the southern part of the state including 24 named fields which produce from the shale (Plate 13). In the period from 1970 to 1975, operators averaged about 10 shale-well completions per year in this area (Figure 37). The last three years, however, have shown a marked increase in shale-well completions due in part to the "energy crisis" and also to the interest by the government in unconventional energy (gas) resources. Figure 37 also shows the distribution of completions in southern West Virginia over the period 1970 to 1977. Most of the completions have been in the western counties of Cabell, Wayne, and Lincoln. However, recent completions in McDowell, Wyoming, and Raleigh Counties are encouraging, indicating that these counties are in areas which appear to have some potential for gas production from the Devonian shale sequence.

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AREAS OF POTENTIAL SHALE GAS PRODUCTION

Future production from the Devonian shale will come from three possible areas. First, and most logical, will be the continued development of existing fields, both within the main producing trend, and in the lesser developed areas of central Wayne County, northern Cabell County, and northern Lincoln County. Deeper drilling in the

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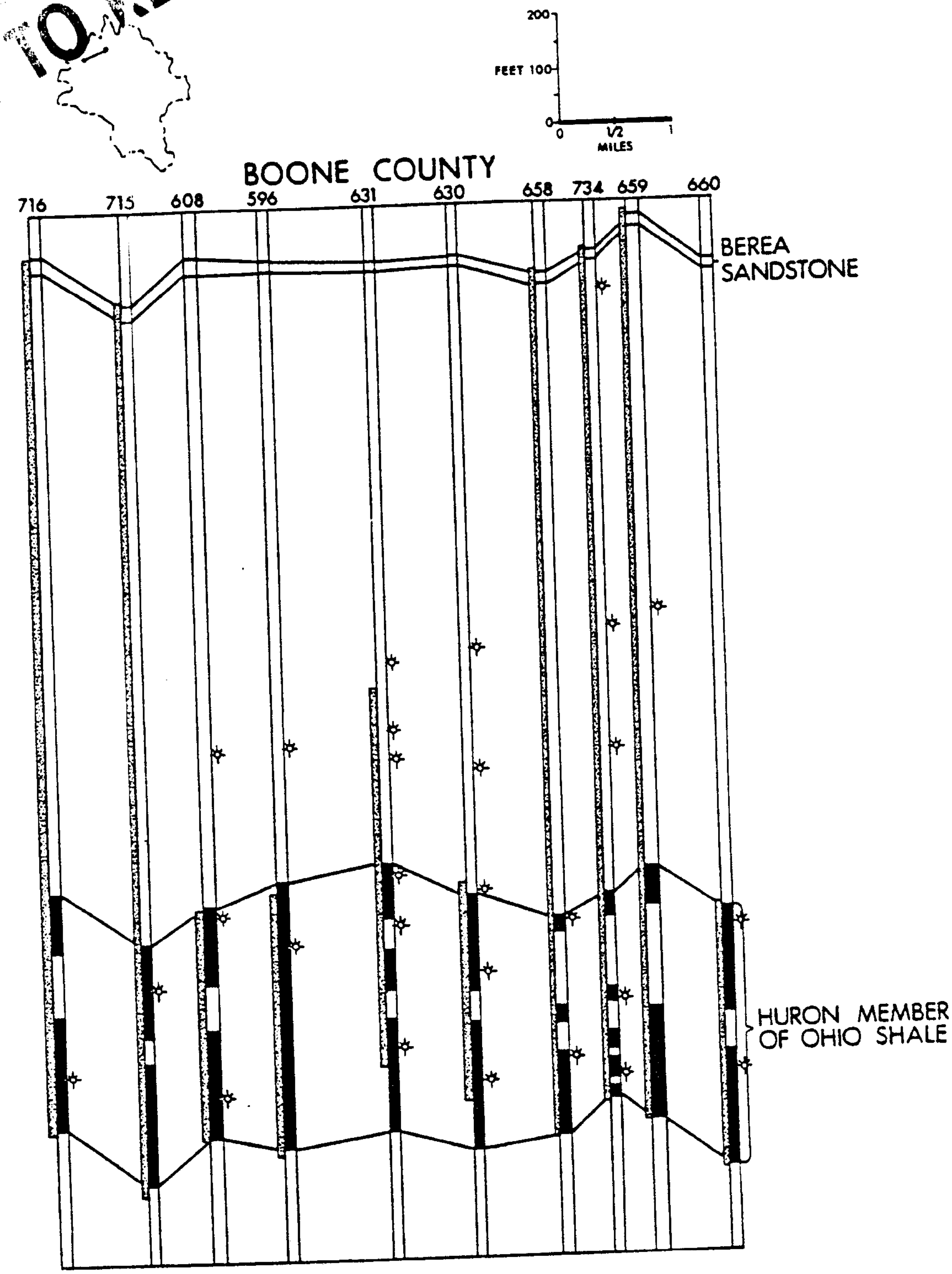
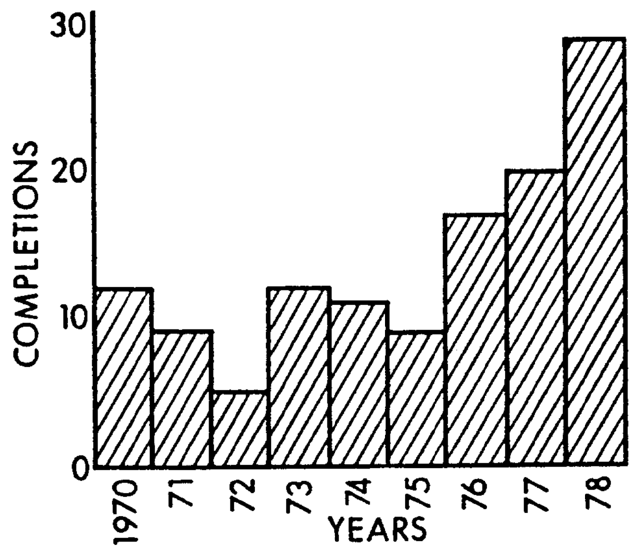


Figure 36. Relation of production to stratigraphy--Boone County. Black shales indicated by solid pattern, shot interval indicated by stippled pattern.



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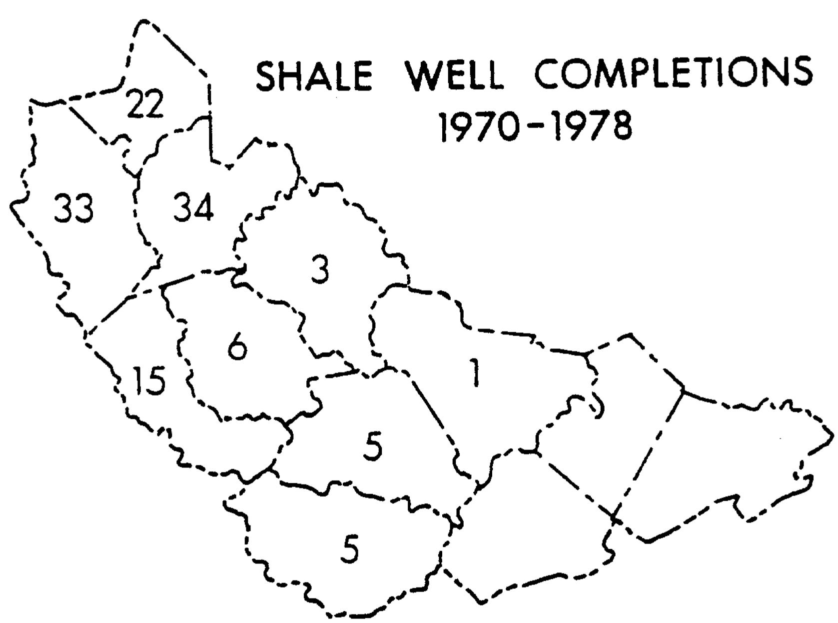

Figure 37. Shale Well Completions, 1970-1978 (after Lytle and others, 1971, 1972, 1973, 1974, 1975, 1976, 1977; Patchen and others, 1978; Patchen, personal communication).

main trend could open up potential new reservoirs in the Rhinestreet and Marcellus Shales.

The second area would be in eastern Boone, Logan, and Mingo Counties for possible exploitation of the Huron Shale. The area east of the Warfield Anticline (Figure 38) and west of approximately the county lines of the above named counties would contain sufficient accumulations of black shale (Plate 14), and fractures associated with the flank of the anticline and possibly reactivation of basement faults, to provide both source beds and avenues for production.

The third area of potential exploitation could be in an area bounded on the west by the Warfield Anticline and on the east by a line through the central part of Raleigh, Wyoming, and McDowell Counties. The potential producing interval would be between the top of the Rhinestreet Shale Member of the West Falls Formation the top of the Onondaga Limestone or the Huntersville Chert. This area provides the greatest thickness of black shale in this interval (Plate 15) and a structural setting which may include fracturing similar to that postulated for the western producing areas. A show of gas from this interval was recorded from a well in north-central McDowell County. As previously indicated, gas shows from this interval are associated with local structures and may be a positive indication of gas producing potential.

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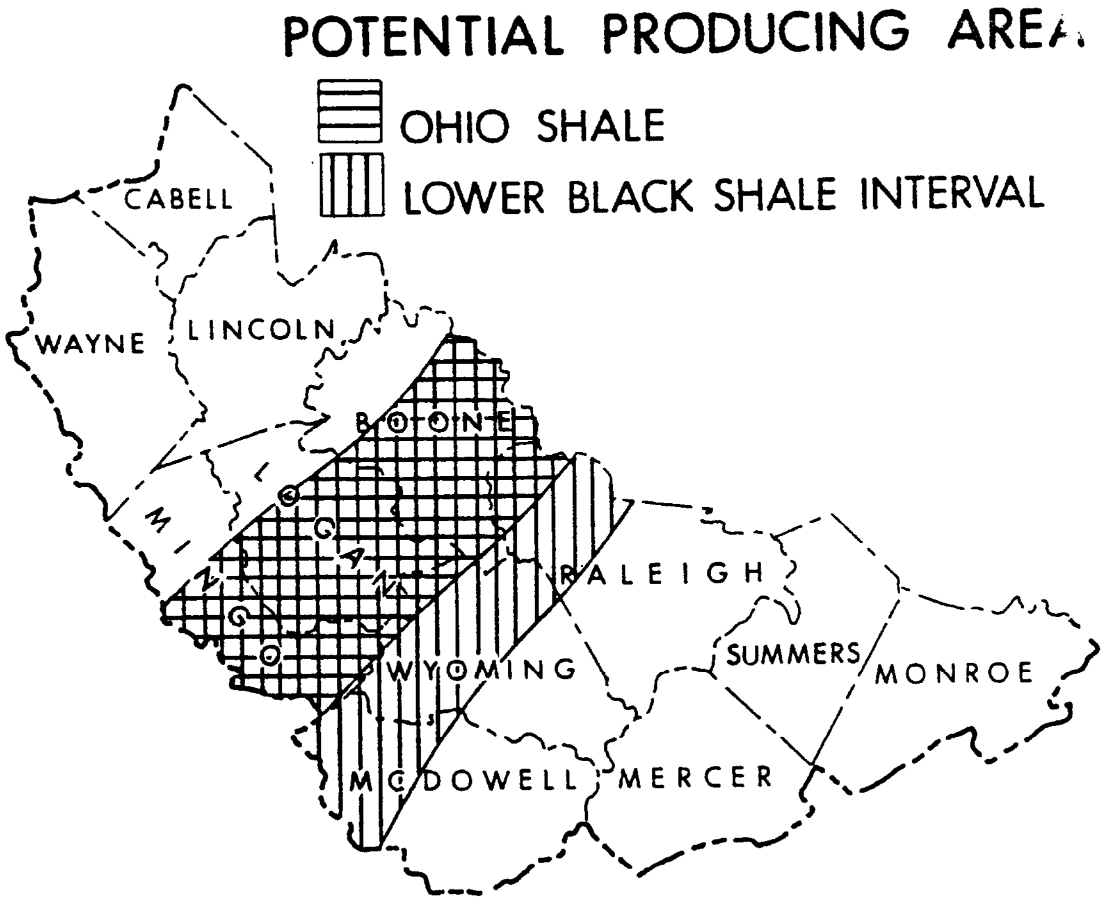
Figure 38



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SUMMARY AND CONCLUSIONS

1. A stratigraphic framework based on New York and Ohio terminology is established for use in the subsurface of southern West Virginia. Recognized stratigraphic units include in ascending order: the Marcellus Shale, Genesee Formation, Sonyea Formation, West Falls Formation,Java Formation, Ohio Shale, and Chagrin Shale. A major unconformity (the Acadian Discontinuity) previously recognized in the subsurface and outcrop of New York and Ohio can be traced across the southern part of the state.

2. The depositional environment of the Middle and Upper Devonian clastic sequence was a shallow epicontinental sea transgressing a surface of eroded carbonates and shale. The southern limit of the depositional basin throughout most of the early part of the Late Devonian was in southern West Virginia. This basin included western shelf-like platforms and received sediments from both eastern and western sources. Black shale developed and was preserved when marine plants flourished and restricted circulation.

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3. Siltstone packets similar to those which produce gas in northern West Virginia have been identified in the southern part of the state and should be explored.

4. A siltstone packet tentatively correlated with the Fifth sand of northern West Virginia and arbitrarily used in the subsurface as the base of the Catskill Formation is correlated with a siltstone at the base of the upper tongue of the Huron Member of the Ohio Shale. If this correlation is accurate, the interval between

the base of the upper tongue of the Huron Member and the top of the Cleveland Member of the Ohio Shale represents the offshore facies equivalent of the Catskill redbeds.

5. The kerogen from which the Devonian shale gas originates is of mixed marine and terrestrial origin and is in the early catagenic stage of hydrocarbon generation. For the type of kerogen present and the stage of maturation, the Devonian shale in southern West Virginia is submature with respect to hydrocarbon generation. The gas produced, however, is of high quality with an average heating value of 1211 Btu. Black shale buried deeper in the basin and subjected to increased temperatures and pressures may be more mature and thus be as good or better a producer than shallower black shale.

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6. The distribution of producing Devonian shale gas wells, reservoir fluid pressure, initial potential, shows in the lower dark shale (Rhinestreet Shale-Marcellus Shale) interval, porosity and permeability of the shale and fractures observed in cores, all strongly suggest that Devonian shale gas is produced from a fractured reservoir.

7. Potential areas of shale gas exploration include eastern Boone, Logan, and Mingo Counties for Huron production and the area between central Boone, Logan, and Mingo Counties on the west, to central Raleigh, Wyoming, and McDowell Counties on the east for production from the Rhinestreet Shale-Marcellus Shale interval.

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APPENDIX A

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GEOCHEMISTRY OF THE DEVONIAN CLASTIC SEQUENCE

Chemical analysis of 690 samples from 19 wells provides information as to the chemical nature of the Devonian clastic sequence in southern West Virginia. From these data, a cross section was constructed to illustrate the lateral variations in mean percentages of elemental oxides (Figures A1 to A14). Silica is represented in Figure A2. The concentration of silica is greater on the eastern and western sides of the basin relative to the concentration in the central part of the basin. Furthermore, in the west, the silica concentration is greater in the black shale than in the non-black shale, whereas, in the east, there is no obvious distinction in the concentrations between lithologies but a general increase in concentration is noted in section. Silica concentrations in the Sonyea Formation increase toward the east and concentrations in the Genesee Formation increase toward the west.

The trend in concentrations of aluminum (Figure A3) in the Angola Shale Member of the West Falls Formation and younger formations is to increase from east to west. In units below the Angola Shale, especially in the Rhinestreet Shale Member of the West Falls Formation, the trend is for the concentrations to increase from west to east. The interval from the Rhinestreet Shale to the Huron Shale shows a shift in high concentrations from the central part of the basin to the western part of the basin. The distribution of potassium shows a trend very similar to that of aluminum.

Sulfur distribution (Figure A5) has a general trend increasing from east to west. The concentration in black shale is greater than in the non-black shale and is higher in the black shale of the Marcellus Shale.

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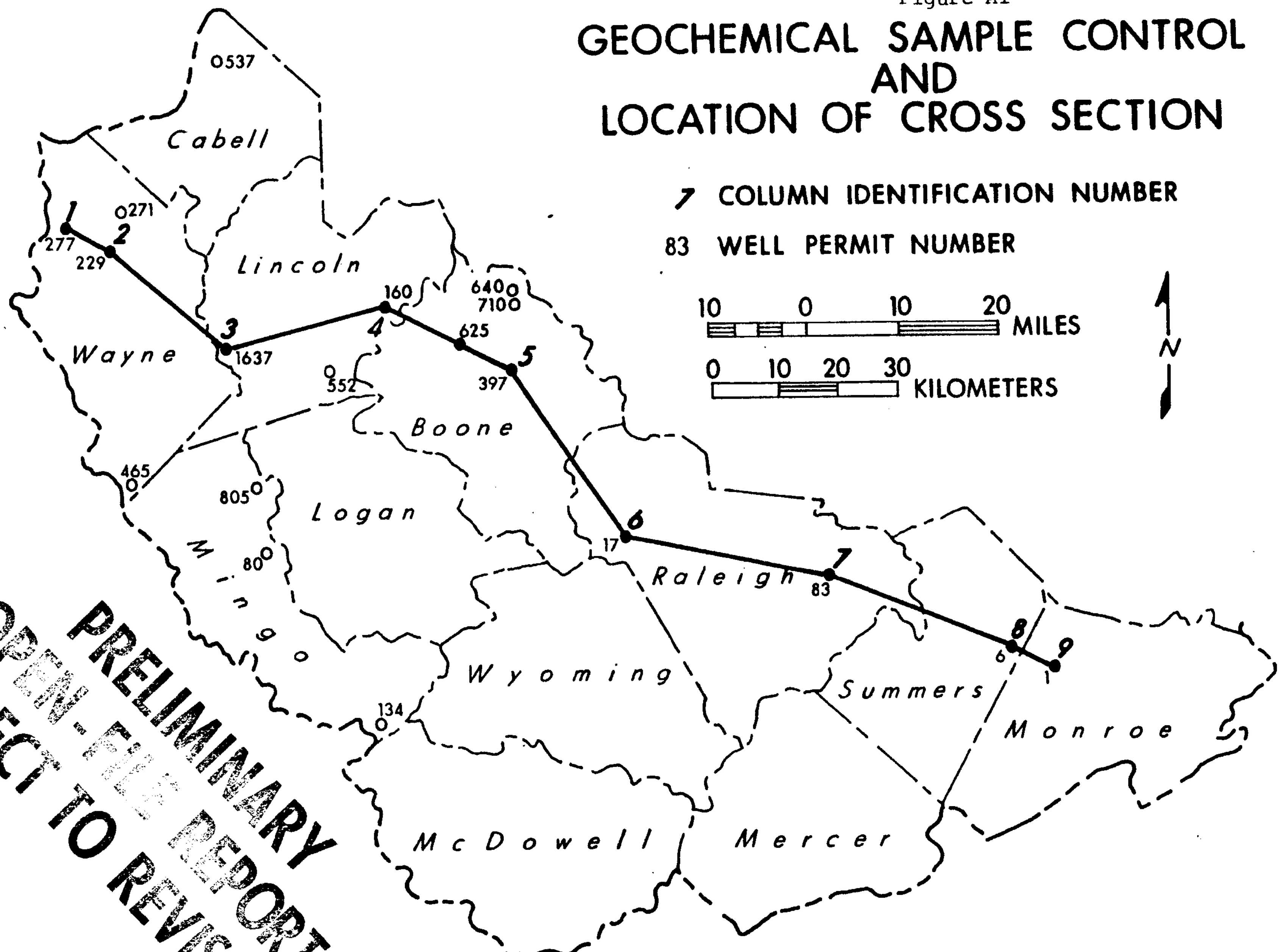
Figure A1

GEOCHEMICAL SAMPLE CONTROL AND LOCATION OF CROSS SECTION



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STRATIGRAPHIC KEY

A--Chagrin Shale and Eastern Equivalents

B--Huron Member of the Ohio Shale

C--Java Formation

D--Angola Shale Member of the West Falls Formation

E--Rhinestreet Shale Member of the West Falls Formation

F--Cashaqua Shale Member of the Sonyea Formation

G--Middlesex Shale Member of the Sonyea Formation

H--West River Shale Member of the Genesee Formation

I--Geneseo Shale Member of the Genesee Formation

J--Marcellus Shale

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WEST	1	2	3	4	5	6	7	8	9	EAST
		62.9	63.4			64.6	68.9	67.5	66.4	A
	66.1	65.0	64.0	63.7	63.7	62.0	66.4	67.3	69.1	B
	63.0	64.0	60.9	62.4	61.9	60.9	65.5	68.3	67.1	C
			61.1		62.1	60.6	65.7	68.4	68.3	D
	63.6	67.1	62.4	61.3	61.2	59.7	62.5	66.4	63.0	E
						61.2	61.7	63.5	62.0	F
						60.4	61.4	62.2	68.6	G
								62.7	61.8	H
							62.6	62.0	61.7	I
							64.7		62.7	J

SiO_2 (%)

Figure A2

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<tr><td></td><td></td><td></td><td></td><td></td><td></td><td>18.8</td><td>16.6</td><td>17.5</td><td>18.8</td><td>F</td></tr>
<tr><td></td><td></td><td></td><td></td><td></td><td></td><td>18.5</td><td>18.3</td><td>18.3</td><td>19.2</td><td>G</td></tr>
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Al_2O_3 (%)

Figure A3

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K_2O (%)

Figure A4

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</table>

S (%)

Figure A5

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Zinc (Figure A6) also shows a distribution which is higher in the black shale. The overall distribution of zinc is similar to that of silica. Calcium concentrations are also very high in the Marcellus Shale (Figure A7). The general trend is for calcium concentrations to increase from east to west. An exception to this trend is seen in the Huron Shale where the highest calcium concentration is found in the center of the basin. Phosphorous concentrations (Figure A8) tend to be very similar across the study area except for a somewhat higher concentration in the Java Formation. Another notable exception is the higher concentration of phosphorous in the Marcellus Shale and in the black shale of that portion of the Rhinestreet Shale which onlaps the unconformity.

Sodium distribution (Figure A9) shows very little variation across the area and superficially resembles the aluminum distribution. The general trend for titanium concentration (Figure A10) is to increase from west to east. Concentrations do seem to be slightly lower in pre-Rhinestreet Shale units than in Rhinestreet Shale and post-Rhinestreet Shale units. Titanium concentrations are low in the Marcellus Shale and that portion of the Rhinestreet Shale which onlaps the unconformity. Manganese (Figure A11) also shows this relationship in the Marcellus Shale and the Rhinestreet Shale. Manganese distribution is similar to that observed for aluminum except that it is lower in the black shale than in the non-black shale. Magnesium (Figure A12) shows no visible trend. Iron (Figure A13) illustrates a trend similar to that of aluminum. Strontium (Figure A14) has a trend similar to that demonstrated for silica with lower values in the center of the

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WEST	1	2	3	4	5	6	7	8	9	EAST
		168	93			70	74	108	150	A
	138	116	93	84	74	66	152	134	154	B
	68	92	57	110	58	61	53	92	114	C
			65		146	135	73	88	172	D
	151	220	92	107	120	103	121	152	222	E
						108	91	202	77	F
						104	57	496	324	G
								94	75	H
							111	105	134	I
							436		220	J

Zn (ppm)

Figure A6

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<tr><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td>1.0</td><td>0.8</td><td>1.7</td><td>I</td></tr>
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</table>

CaO (%)

Figure A7

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<tr><td></td><td></td><td></td><td></td><td></td><td></td><td>0.15</td><td>0.12</td><td>0.14</td><td>0.13</td><td>F</td></tr>
<tr><td></td><td></td><td></td><td></td><td></td><td></td><td>0.14</td><td>0.14</td><td>0.14</td><td>4.86</td><td>G</td></tr>
<tr><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td>0.14</td><td>0.14</td><td>H</td></tr>
<tr><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td>0.14</td><td>0.13</td><td>0.17</td><td>I</td></tr>
<tr><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td>0.26</td><td></td><td>0.26</td><td>J</td></tr>
</table>

P_2O_5 (%)

Figure A8

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WEST	1	2	3	4	5	6	7	8	9	EAST
		0.69	0.74			0.66	0.72	0.72	0.74	A
	0.80	0.69	0.78	0.83	0.78	0.77	0.75	0.73	0.74	B
	0.70	0.66	0.76	0.77	0.79	0.75	0.74	0.74	0.76	C
			0.77		0.78	0.76	0.74	0.72	0.73	D
	0.62	0.67	0.77	0.81	0.78	0.82	0.78	0.75	0.79	E
						0.79	0.68	0.77	0.78	F
						0.82	0.78	0.79	0.83	G
								0.76	0.76	H
							0.79	0.75	0.78	I
							0.83		0.75	J

Na_2O (%)

Figure A9

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<table>
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<tr><td></td><td>1.04</td><td>1.07</td><td>1.11</td><td>1.18</td><td>1.19</td><td>1.23</td><td>1.27</td><td>1.22</td><td>1.24</td><td>B</td></tr>
<tr><td></td><td rowspan="2">1.09</td><td rowspan="2">1.08</td><td>1.10</td><td rowspan="2">1.12</td><td>1.16</td><td>1.52</td><td>1.25</td><td>1.18</td><td>1.26</td><td>C</td></tr>
<tr><td></td><td>1.08</td><td>1.13</td><td>1.24</td><td>1.01</td><td>1.16</td><td>1.22</td><td>D</td></tr>
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<tr><td></td><td></td><td></td><td></td><td></td><td></td><td>1.01</td><td>1.18</td><td>1.21</td><td>1.25</td><td>F</td></tr>
<tr><td></td><td></td><td></td><td></td><td></td><td></td><td>0.94</td><td>1.14</td><td>1.18</td><td>1.07</td><td>G</td></tr>
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<tr><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td>1.01</td><td>1.22</td><td>1.05</td><td>I</td></tr>
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TiO_2 (%)

Figure A10

PRELIMINARY
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<tr><td></td><td></td><td>0.09</td><td>0.09</td><td></td><td></td><td>0.08</td><td>0.06</td><td>0.06</td><td>0.07</td><td>A</td></tr>
<tr><td></td><td>0.03</td><td>0.04</td><td>0.05</td><td>0.06</td><td>0.07</td><td>0.11</td><td>0.07</td><td>0.07</td><td>0.07</td><td>B</td></tr>
<tr><td></td><td rowspan="2">0.08</td><td rowspan="2">0.09</td><td>0.15</td><td rowspan="2">0.09</td><td>0.09</td><td>0.14</td><td>0.09</td><td>0.10</td><td>0.07</td><td>C</td></tr>
<tr><td></td><td>0.13</td><td>0.09</td><td>0.10</td><td>0.06</td><td>0.10</td><td>0.06</td><td>D</td></tr>
<tr><td></td><td>0.04</td><td>0.02</td><td>0.02</td><td>0.03</td><td>0.05</td><td>0.13</td><td>0.06</td><td>0.09</td><td>0.05</td><td>E</td></tr>
<tr><td></td><td></td><td></td><td></td><td></td><td></td><td>0.09</td><td>0.08</td><td>0.11</td><td>0.08</td><td>F</td></tr>
<tr><td></td><td></td><td></td><td></td><td></td><td></td><td>0.04</td><td>0.10</td><td>0.11</td><td>0.06</td><td>G</td></tr>
<tr><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td>0.09</td><td>0.07</td><td>H</td></tr>
<tr><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td>0.05</td><td>0.08</td><td>0.05</td><td>I</td></tr>
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</table>

MnO (%)

Figure A11

PRELIMINARY
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<tr><td></td><td rowspan="2">2.2</td><td rowspan="2">2.0</td><td>1.9</td><td rowspan="2">2.0</td><td>1.9</td><td>2.3</td><td>1.6</td><td>1.5</td><td>1.4</td><td>C</td></tr>
<tr><td></td><td>1.9</td><td>2.1</td><td>1.8</td><td>1.8</td><td>1.7</td><td>1.6</td><td>D</td></tr>
<tr><td></td><td>2.3</td><td>1.6</td><td>1.5</td><td>1.8</td><td>2.1</td><td>1.8</td><td>1.8</td><td>1.7</td><td>1.6</td><td>E</td></tr>
<tr><td></td><td></td><td></td><td></td><td></td><td></td><td>2.3</td><td>2.1</td><td>1.8</td><td>1.9</td><td>F</td></tr>
<tr><td></td><td></td><td></td><td></td><td></td><td></td><td>1.9</td><td>2.3</td><td>2.1</td><td>2.3</td><td>G</td></tr>
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<tr><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td>1.9</td><td>2.1</td><td>2.1</td><td>I</td></tr>
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</table>

Mg O (%)

Figure A12

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WEST	1	2	3	4	5	6	7	8	9	EAST
		9.2	9.4			12.1	7.7	7.6	7.8	A
	7.7	7.7	8.5	9.0	9.4	10.4	7.2	7.7	8.1	B
	7.5	7.4	9.6	8.8	9.4	16.2	9.2	8.1	8.0	C
			9.1		9.6	11.9	8.6	8.0	7.8	D
	6.7	6.9	8.0	9.8	9.6	11.5	9.7	8.5	9.4	E
						8.8	9.3	9.9	9.7	F
						11.1	9.8	9.4	1.9	G
								9.0	9.4	H
							10.3	8.8	8.5	I
							9.1		8.1	J

Fe_2O_3 (%)

Figure A13

PRELIMINARY
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<table>
<tr><th>WEST</th><th>1</th><th>2</th><th>3</th><th>4</th><th>5</th><th>6</th><th>7</th><th>8</th><th>9</th><th>EAST</th></tr>
<tr><td></td><td></td><td>78</td><td>50</td><td></td><td></td><td>70</td><td>87</td><td>105</td><td>76</td><td>A</td></tr>
<tr><td></td><td>103</td><td>108</td><td>76</td><td>58</td><td>58</td><td>106</td><td>100</td><td>86</td><td>75</td><td>B</td></tr>
<tr><td></td><td rowspan="2">143</td><td rowspan="2">118</td><td>105</td><td rowspan="2">86</td><td>68</td><td>57</td><td>83</td><td>78</td><td>85</td><td>C</td></tr>
<tr><td></td><td>111</td><td>61</td><td>60</td><td>92</td><td>98</td><td>75</td><td>D</td></tr>
<tr><td></td><td>100</td><td>125</td><td>66</td><td>67</td><td>35</td><td>77</td><td>103</td><td>104</td><td>106</td><td>E</td></tr>
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<tr><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td>100</td><td>70</td><td>H</td></tr>
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</table>

Sr (ppm)

Figure A14

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basin and higher on the periphery.

Variation diagrams (Figures A15 and A16) were constructed representing mean values of concentrations of each stratigraphic interval represented. Silica concentrations increase up section as do the concentrations of titanium. Complimentary to this trend is that of potassium and magnesium. Other elements may show a slight decrease up section but these are not as obvious as those mentioned. Several elements may be grouped together based on the shape of the curves of the variation diagrams. Sulfur and zinc are similar and calcium and phosphorous are similar. Titanium, manganese, magnesium, and iron seem to have similarly shaped curves as well.

To compare distributions of elemental concentrations between black shale and non-black shale, a series of maps were constructed representing the trend of each element relative to the mean concentration of that element in the Huron Shale. Four intervals were chosen for comparison: the Ohio Shale and the Rhinestreet Shale Member of the West Falls Formation (black shale facies) and the "White Slate" interval (Java Formation and Angola Shale Member of the West Falls Formation) and the Chagrin Shale and undifferentiated Devonian shale (non-black shale and siltstone facies). Values above the mean concentration for the Huron Shale are referred to as "high" (screened areas on maps) and those below the mean concentration are referred to as "low".

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Silica content in the non-black shale is greatest in the easternmost part of the study area (Figure A17). The black shale shows no consistent pattern except that there is an area of high silica concentration in the west as well as the east. The distribution of aluminum

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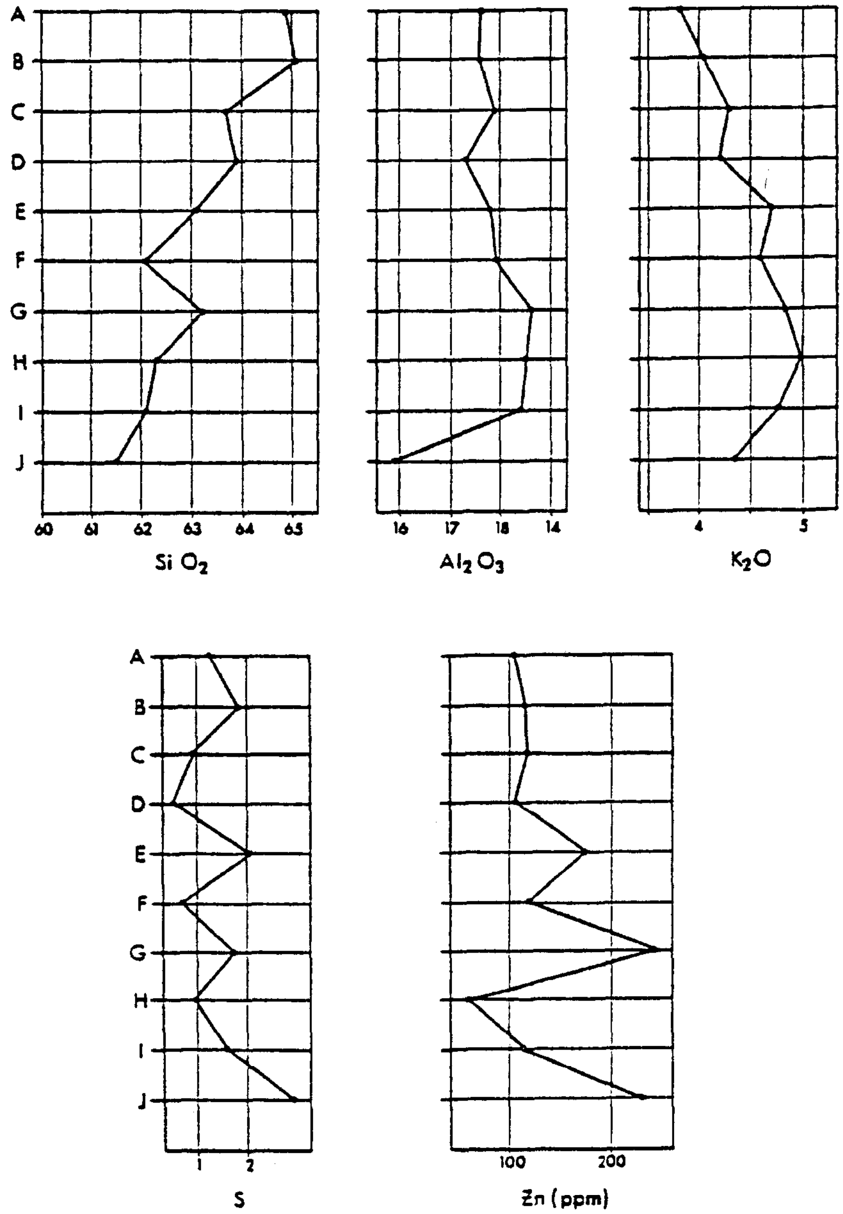

Figure A15

PRELIMINARY
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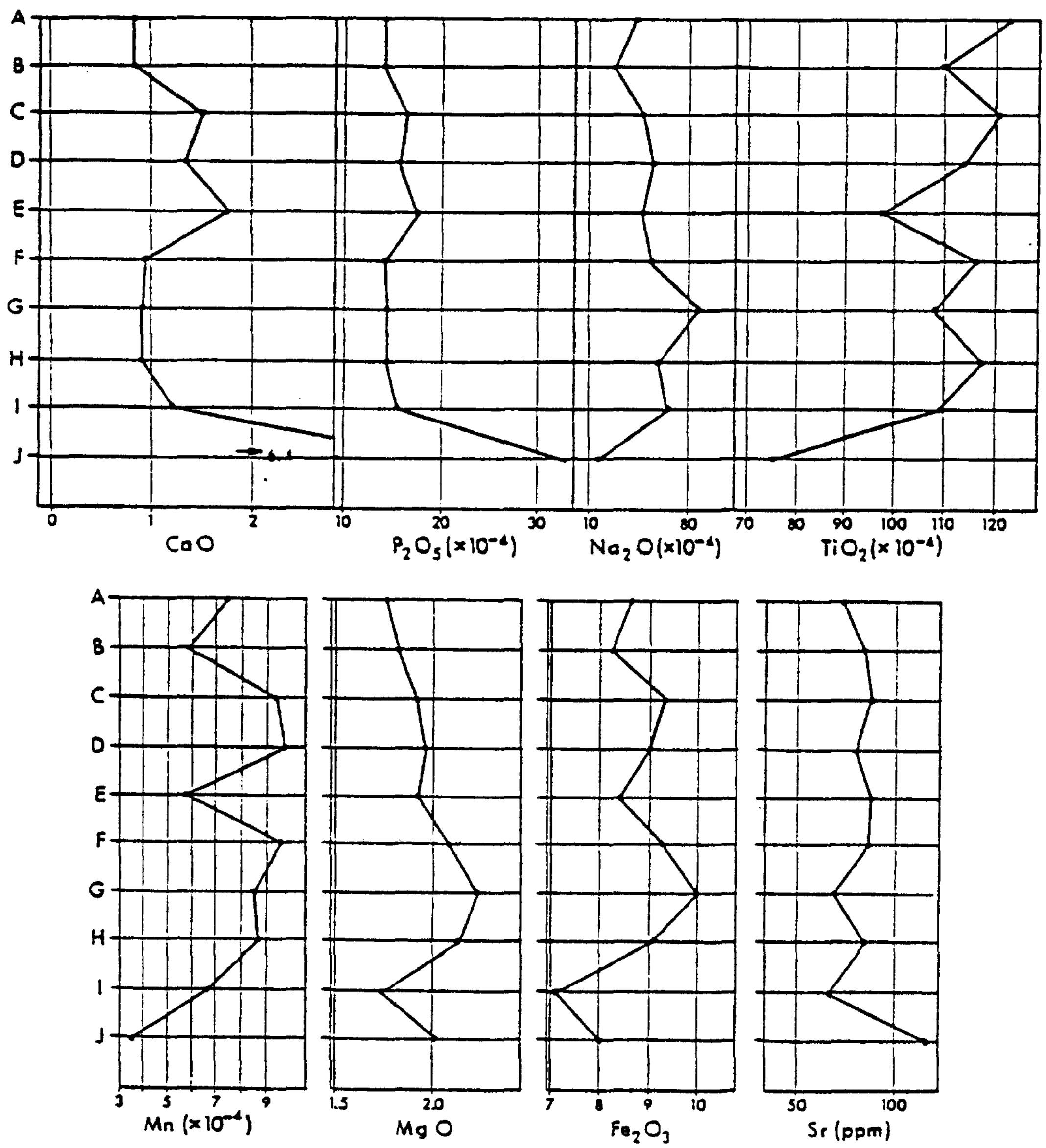

Figure A16

PRELIM ARY
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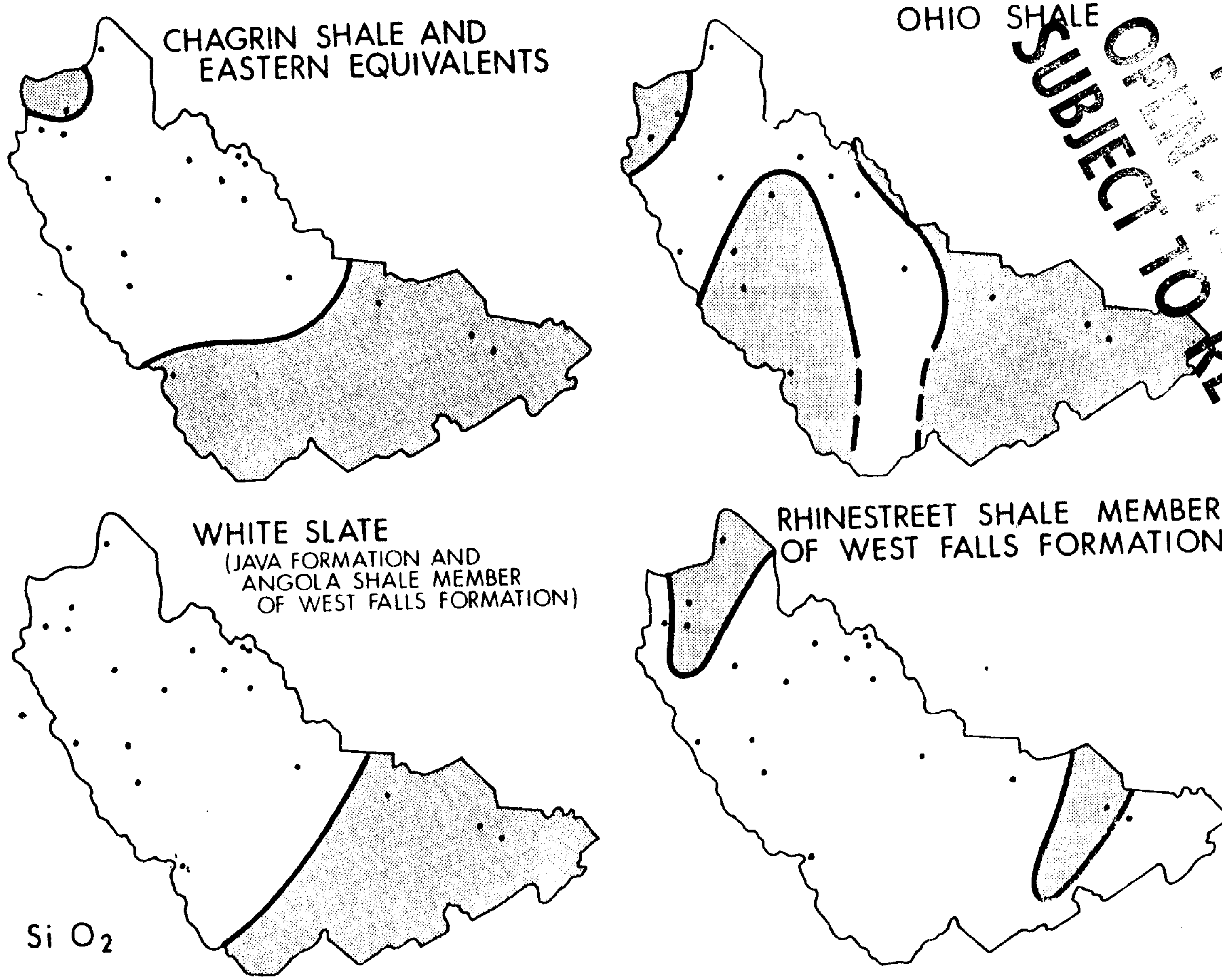

Figure A17

(Figure A18) shows no preference for lithology. A shift in mean concentration from the east to west is seen up section with the higher concentrations being in the western sector. The distribution of potassium (Figure A19) is very similar to that of aluminum showing no preference for lithology and a shift in mean concentration.

High sulfur concentrations tend to be associated primarily with the black shale (Figure A20). High concentrations in the black shale are found consistently in the western portion of the study area. Zinc concentrations (Figure A21) are higher in the black shale than in the non-black shale. High concentrations are found on either side of the basin and along the axis of the Warfield Anticline.

Concentrations of calcium (Figure A22) and phosphorous (Figure A23) do not show any correlation with lithology. They do, however, show a greater distribution of higher concentrations in the two stratigraphically lower units. Concentrations of sodium (Figure A24) tend to decrease up section but do not show a systematic shift in mean concentration. Titanium concentrations (Figure A25) show no preference for lithology but do show a shift in mean concentration to the west. High concentrations are found primarily in the eastern portion of the study area.

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Manganese (Figure A26) shows a greater distribution of high concentrations in the non-black shale and in the eastern portion of the black shale. High magnesium concentrations (Figure A27) are found in the western part of the study area in all lithologies. There is no preference for lithology seen in the distribution of iron (Figure A28). There does seem to be a correlation of low concentrations with the location of the Warfield Anticline. Strontium also shows no correlation with

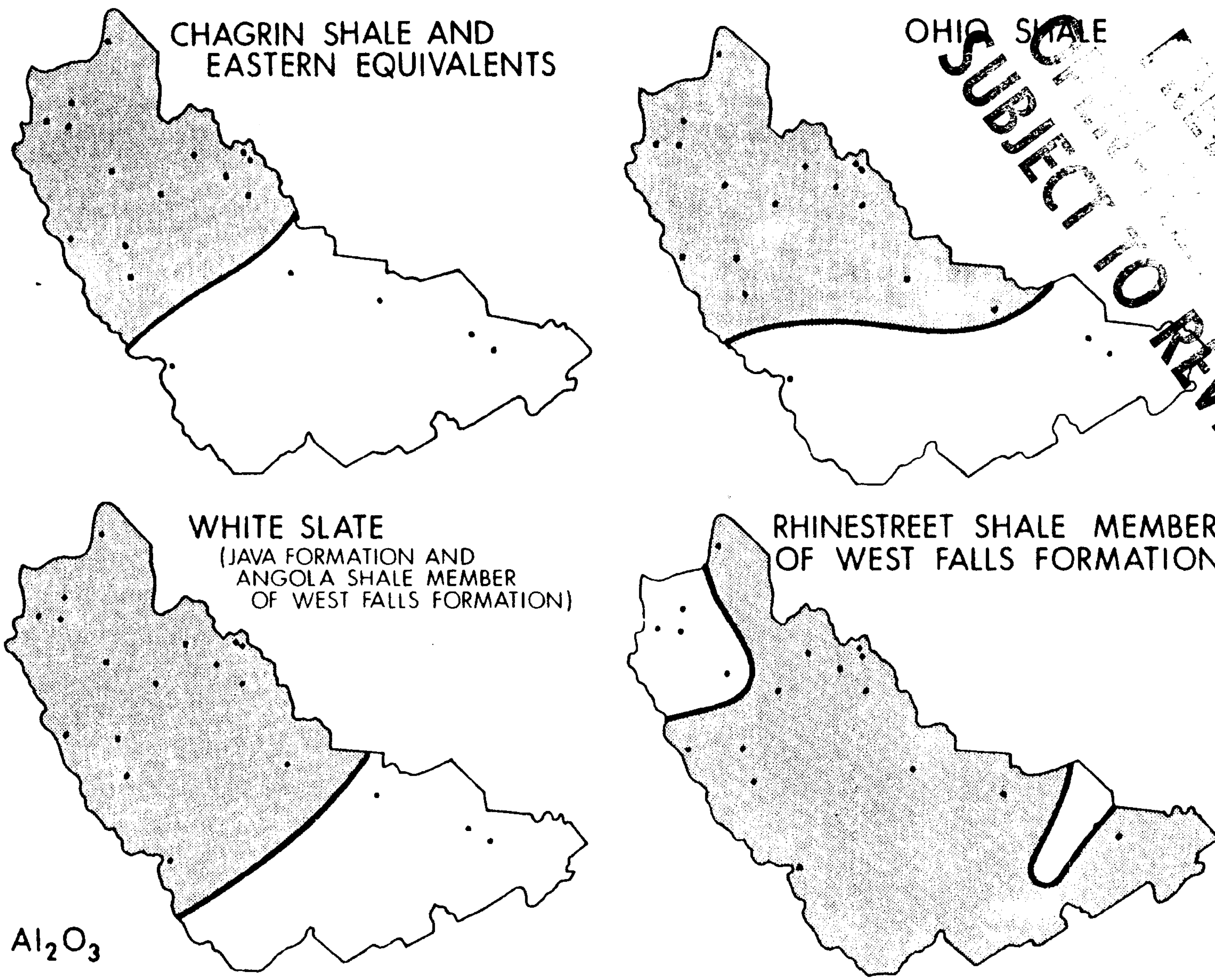

Figure A18

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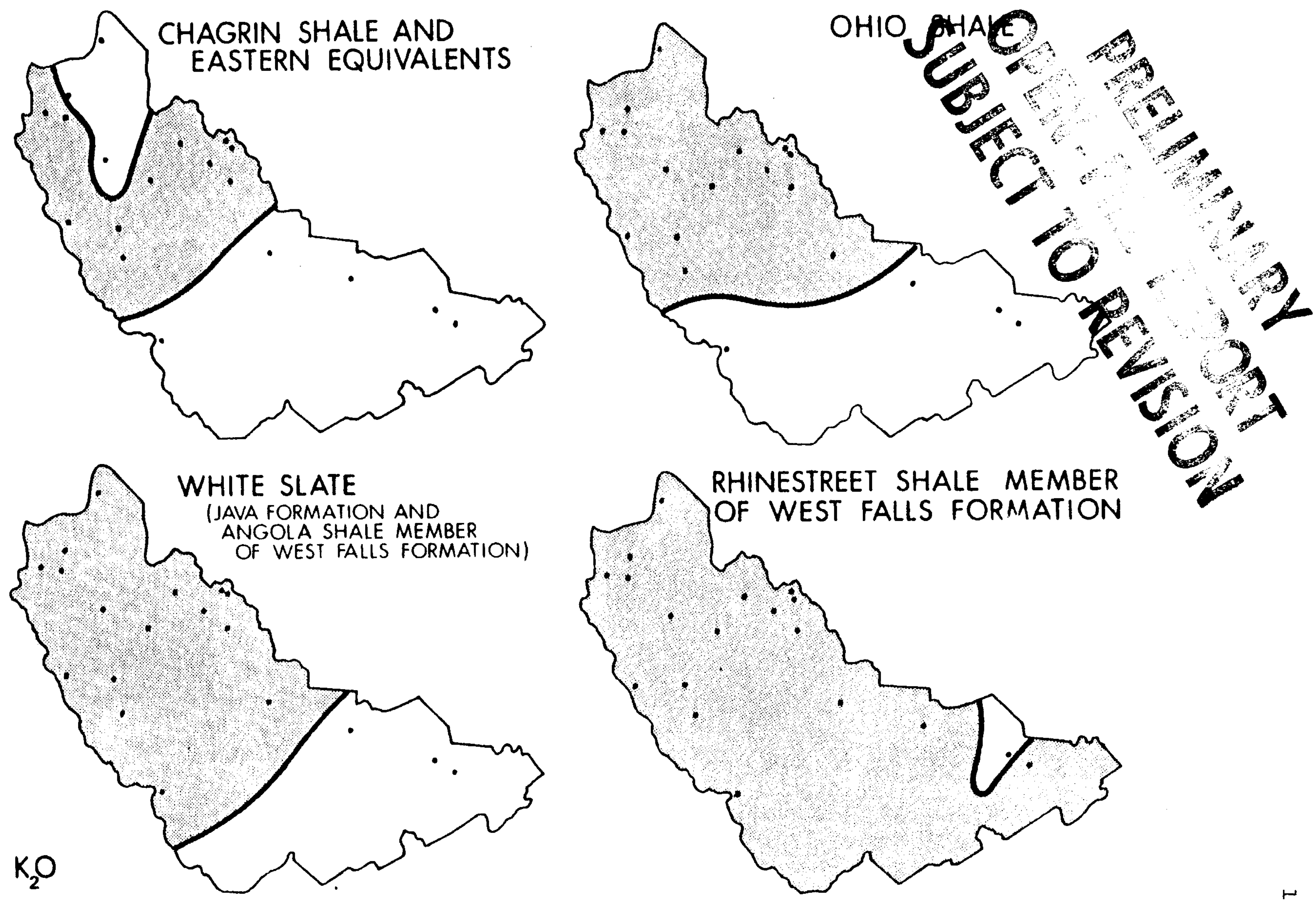
CHAGRIN SHALE AND
EASTERN EQUIVALENTS
OHIO SHALE
PRELIMINARY
OPEN-FILE REPORT
SUBJECT TO REVISION
WHITE SLATE
(JAVA FORMATION AND
ANGOLA SHALE MEMBER
OF WEST FALLS FORMATION)
RHINESTREET SHALE MEMBER
OF WEST FALLS FORMATION
K_2O

Figure A19

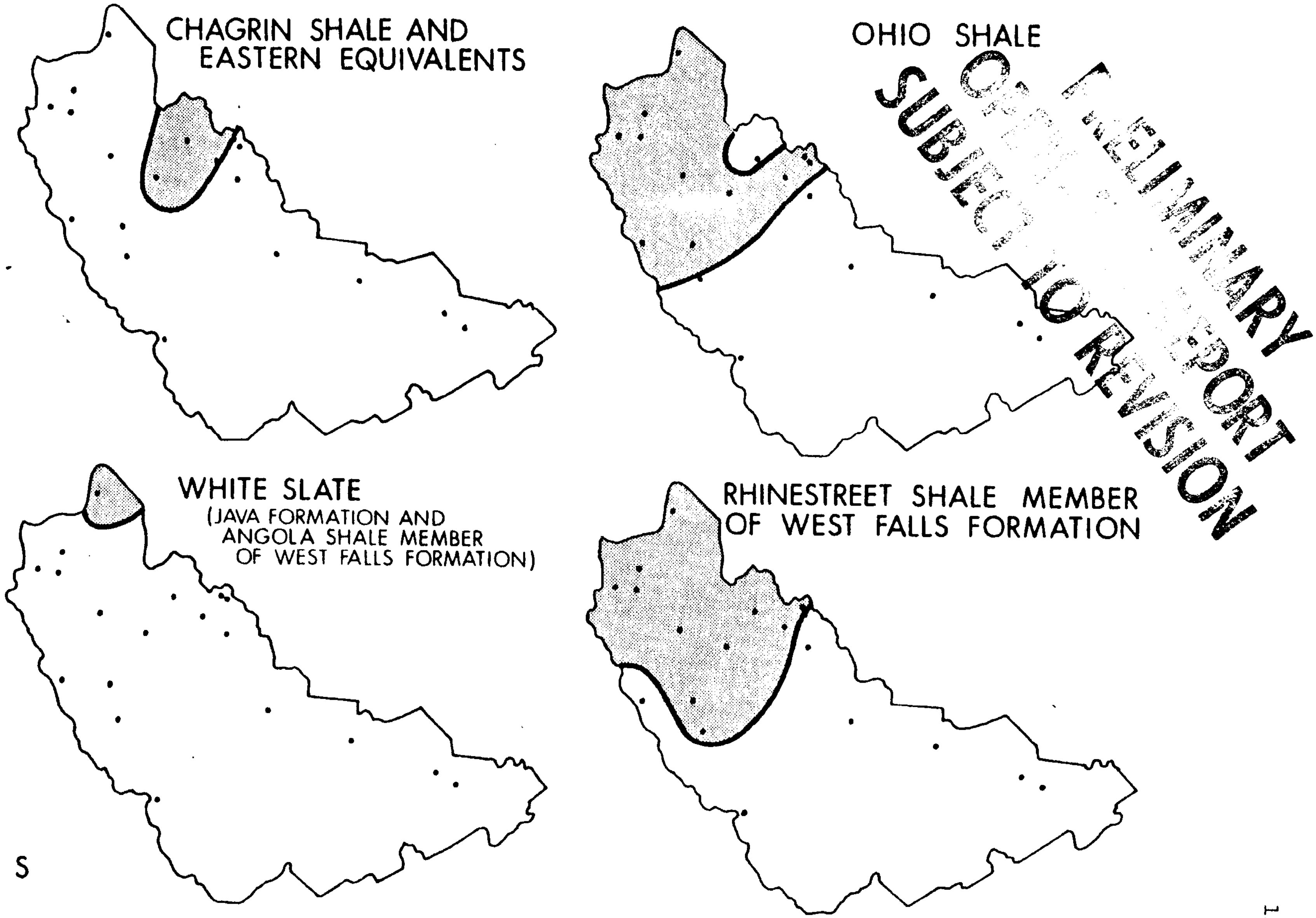

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Figure A20

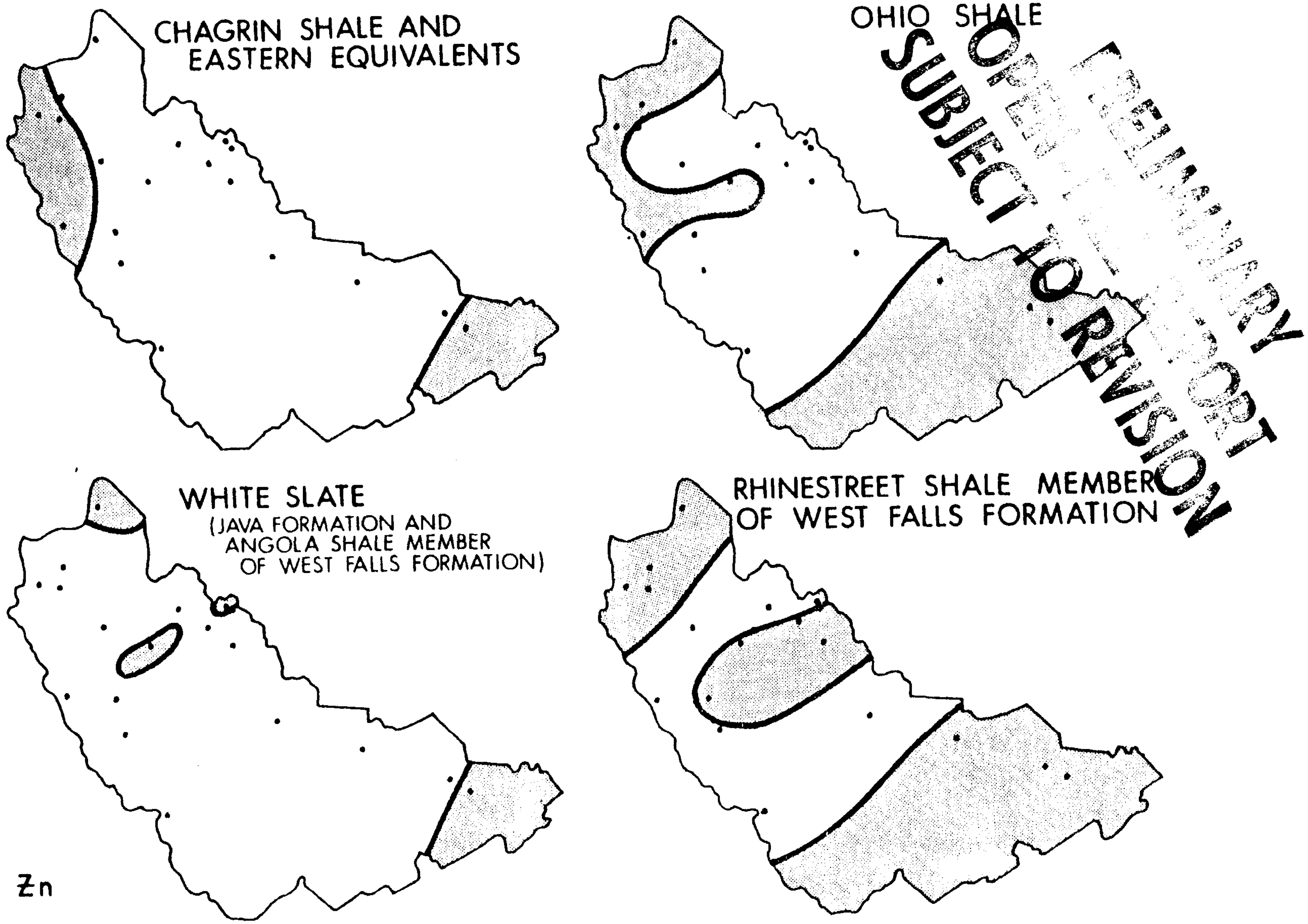

Figure A21

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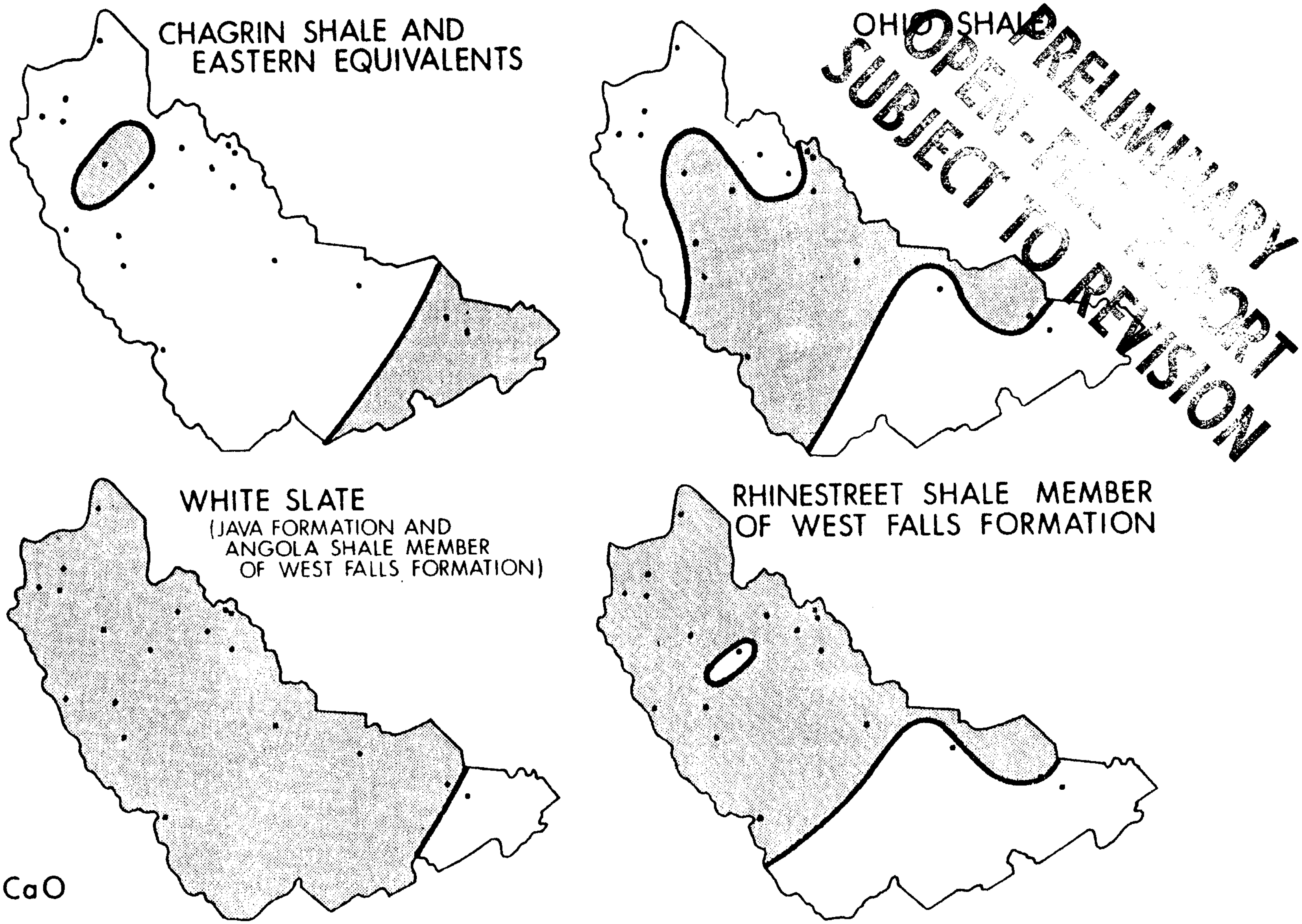
CHAGRIN SHALE AND
EASTERN EQUIVALENTS
OHIO SHALE
WHITE SLATE
(JAVA FORMATION AND
ANGOLA SHALE MEMBER
OF WEST FALLS FORMATION)
RHINESTREET SHALE MEMBER
OF WEST FALLS FORMATION
CaO
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Figure A22

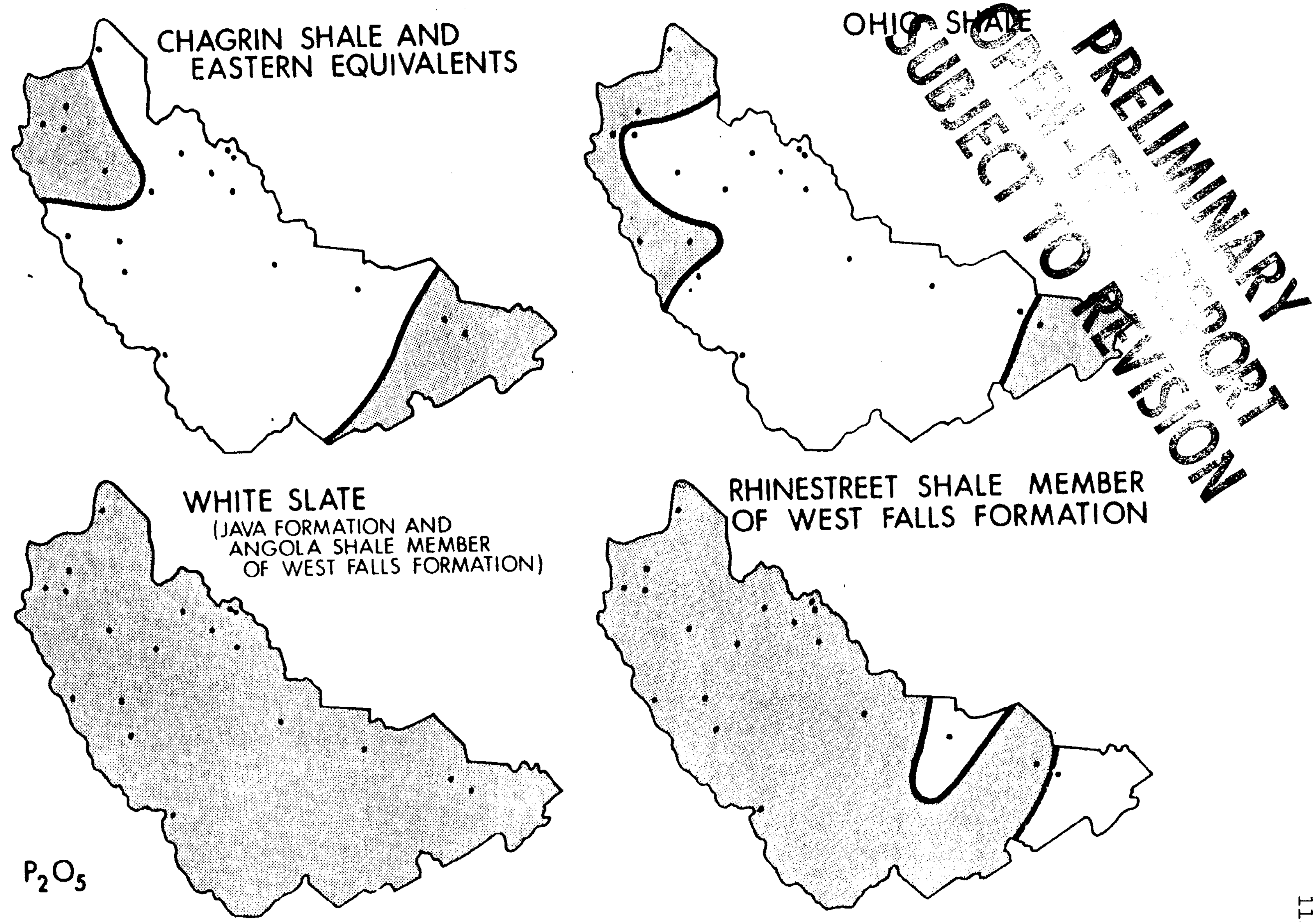
CHAGRIN SHALE AND
EASTERN EQUIVALENTS
OHIO SHALE
PRELIMINARY
SUBJECT TO REVISION
WHITE SLATE
(JAVA FORMATION AND
ANGOLA SHALE MEMBER
OF WEST FALLS FORMATION)
RHINESTREET SHALE MEMBER
OF WEST FALLS FORMATION
P_2O_5

Figure A23

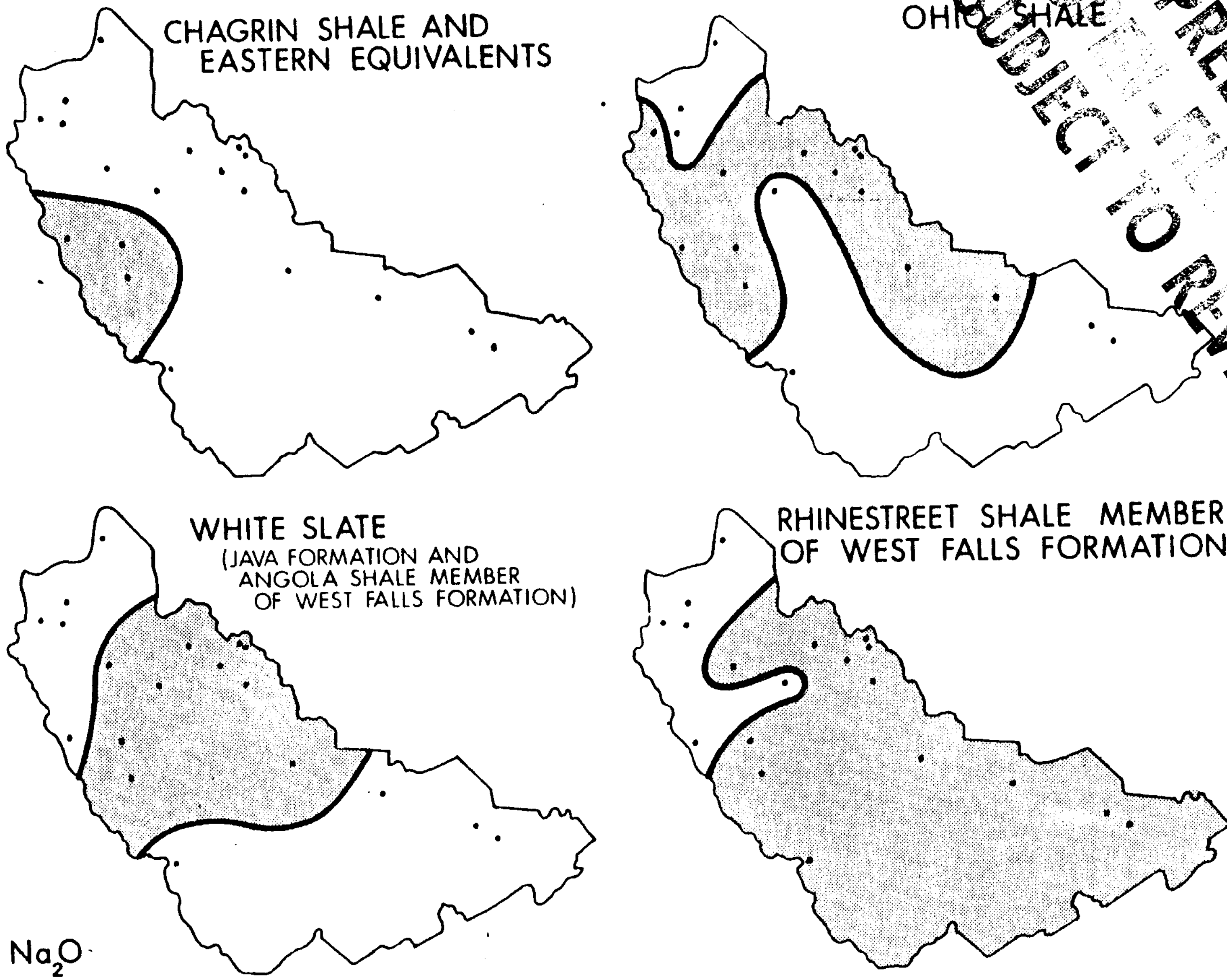

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Figure A24

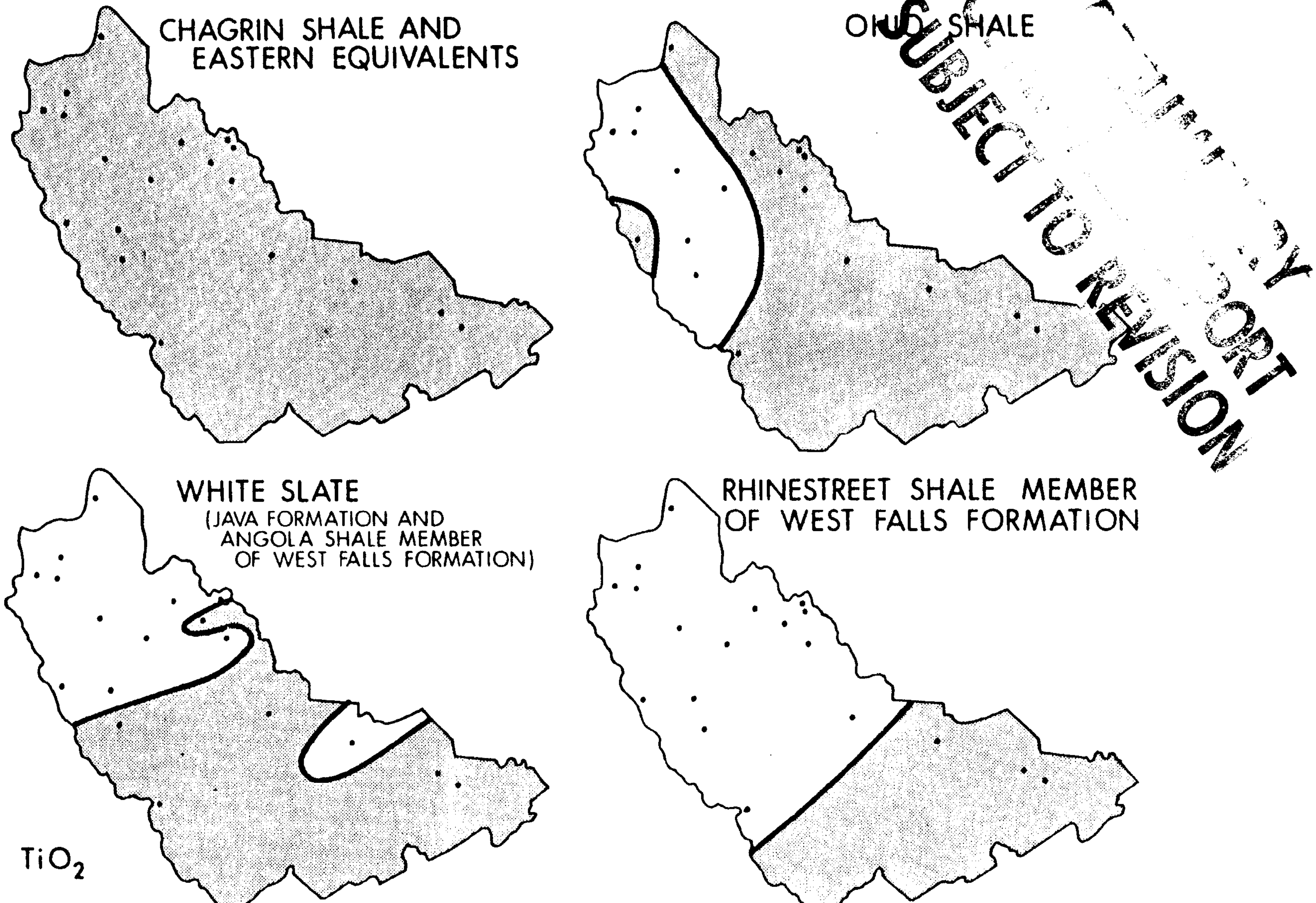

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Figure A25

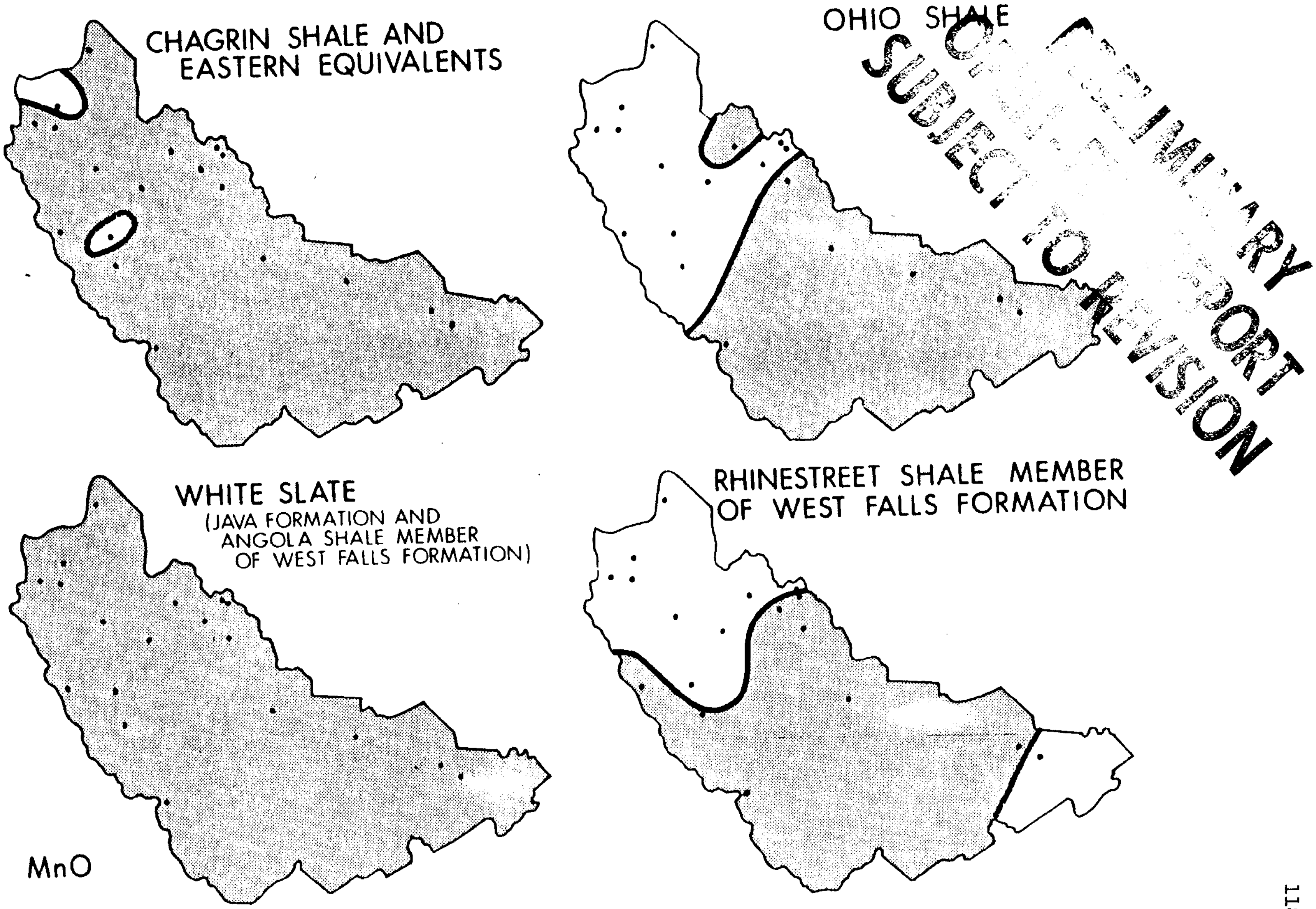
CHAGRIN SHALE AND
EASTERN EQUIVALENTS
OHIO SHALE
WHITE SLATE
(JAVA FORMATION AND
ANGOLA SHALE MEMBER
OF WEST FALLS FORMATION)
RHINESTREET SHALE MEMBER
OF WEST FALLS FORMATION
MnO

Figure A26

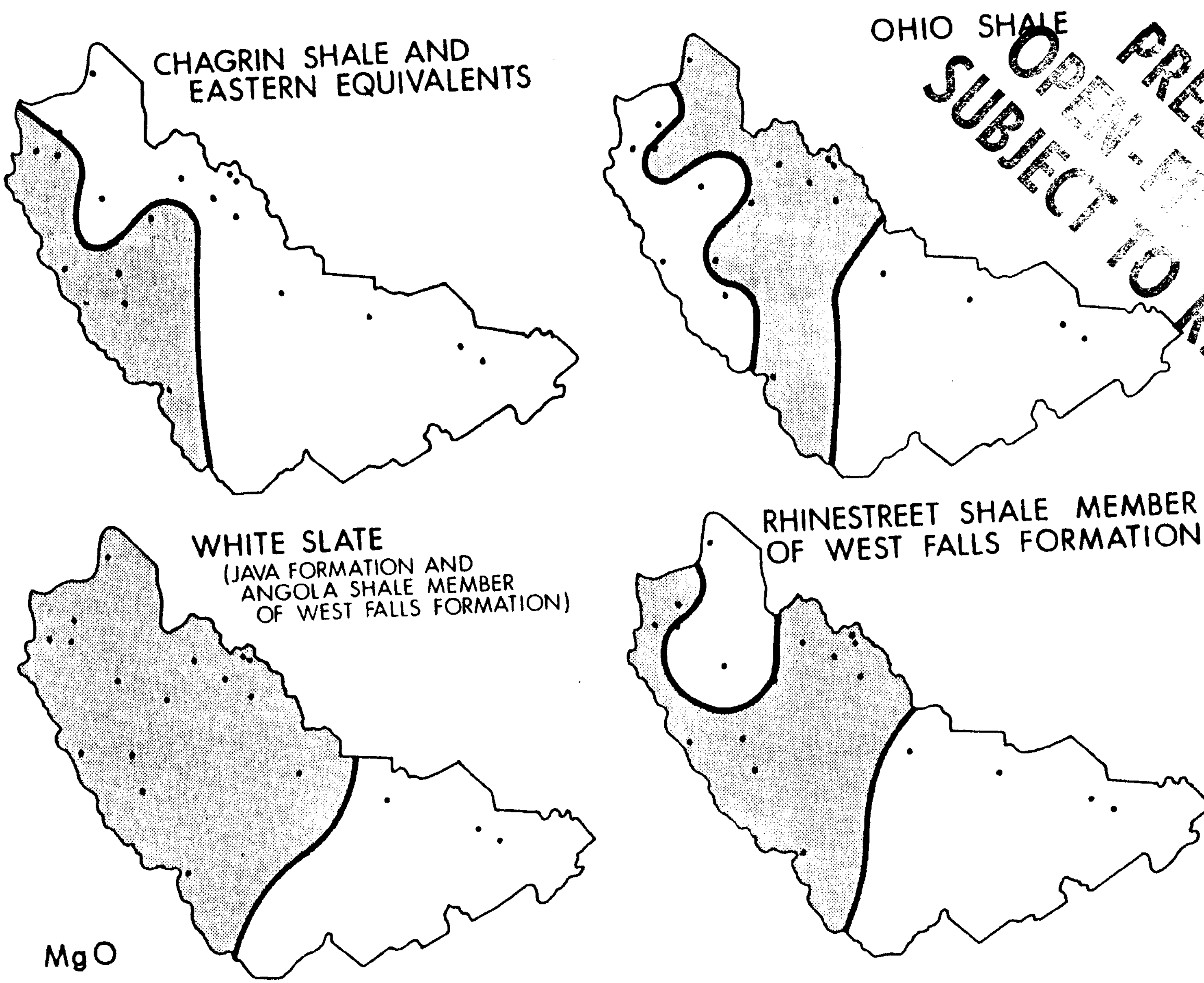

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Figure A27

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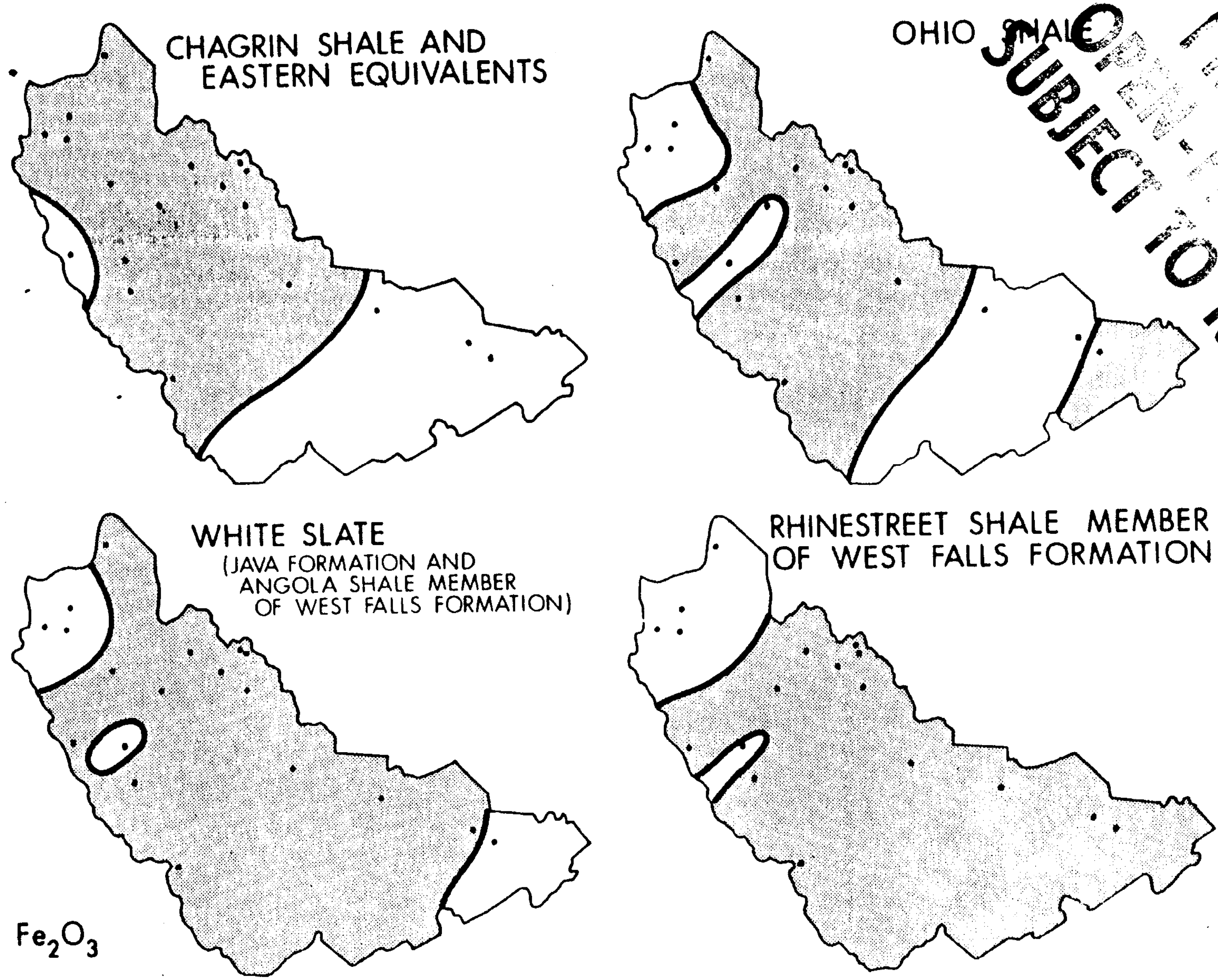

Figure A28

lithology (Figure A29) and there seems to be a possible correlation between high concentrations and the location of the Warfield Anticline.

The silica concentration in the black shale shows high concentrations in both the east and the west. This would suggest the possibility of both an eastern and a western source for the silica. The most common source of silica would be found with the quartz fraction of the detrital mineral suite. The distribution of quartz is seen in Figure A30. No correlation between quartz and the high silica concentration in the west can be recognized. The high silica concentration may, however, be related to an influx of clay minerals from the erosional surface to the west. The higher concentrations of aluminum and potassium in the west would support this idea of a western source for fine-grained clastics.

The great concentration of sulfur in the black shale of the western portion of the study area indicates a strong correlation of sulfur with the areas of massive black shale accumulation. The sulfur is found most commonly in combination with iron as the mineral pyrite or similar iron sulfide species. Zinc concentrations in the black shale seems to be associated with what are interpreted to be shallower areas of black shale accumulation such as the extreme western portion of the study area and along the crest of the Warfield Anticline, and possibly in the eastern portion of the study area. Phosphate may be related to the shallower areas of black shale deposition as well. The distribution of phosphate and zinc in the Huron Shale are very similar but the similarity in distributions in the Rhinestreet Shale are not seen. This difference can be explained in that the western area of Rhinestreet

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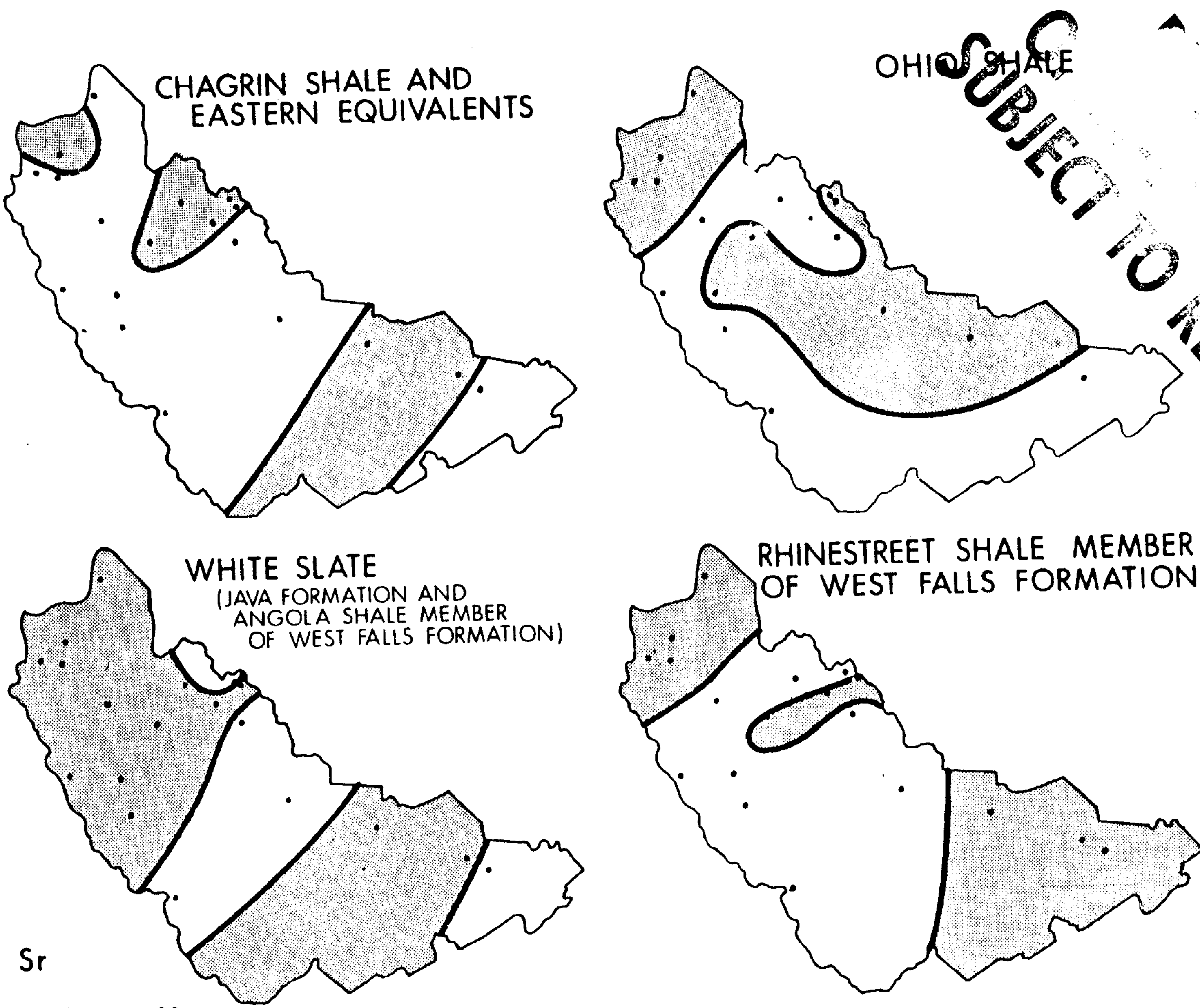

Figure A29

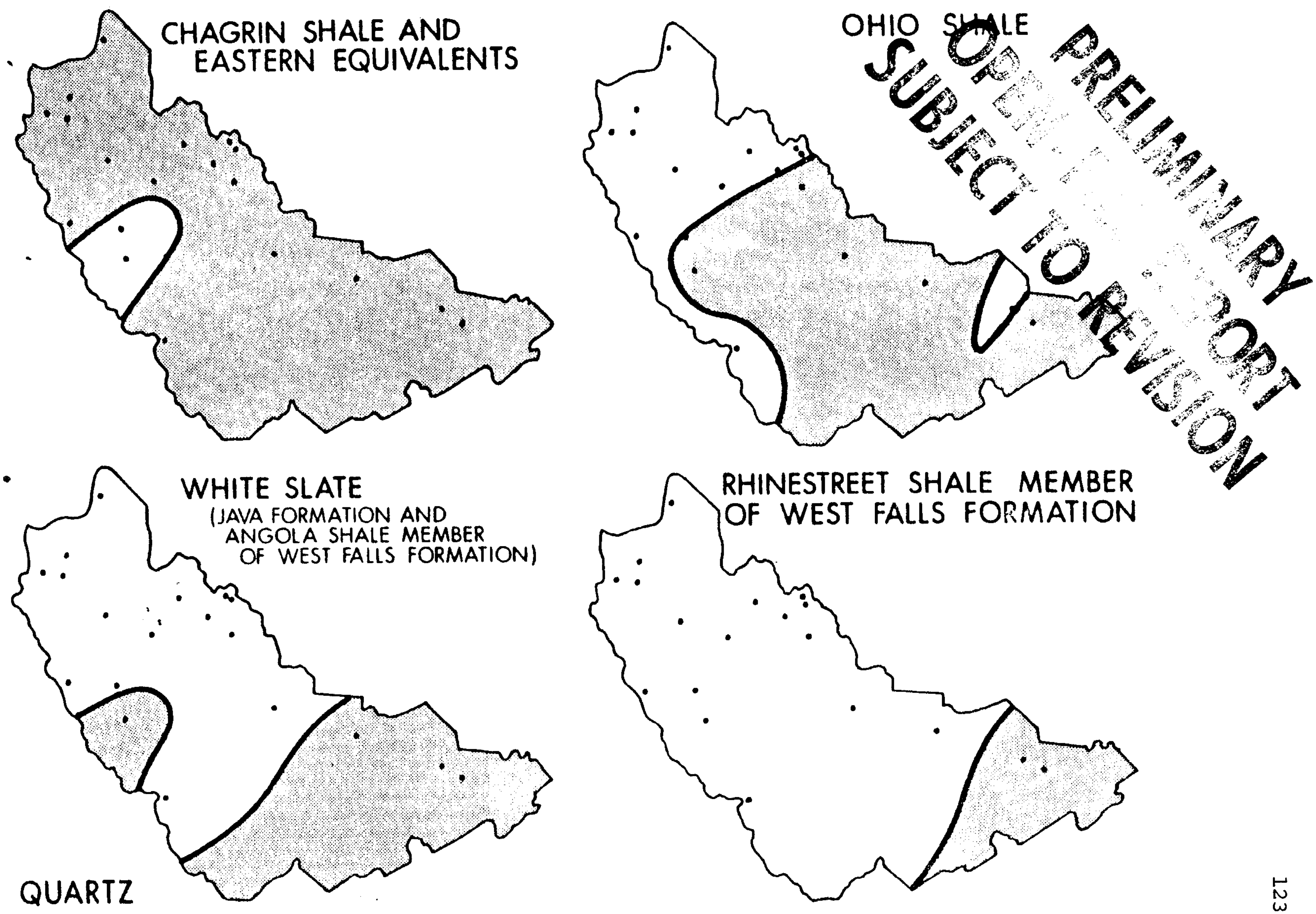
CHAGRIN SHALE AND
EASTERN EQUIVALENTS
OHIO SHALE
PRELIMINARY
OPEN FILE REPORT
SUBJECT TO REVISION
WHITE SLATE
(JAVA FORMATION AND
ANGOLA SHALE MEMBER
OF WEST FALLS FORMATION)
RHINESTREET SHALE MEMBER
OF WEST FALLS FORMATION
QUARTZ

Figure A30

Shale deposition was on a surface of erosion which may account for the greater concentration of phosphate. A similar high concentration of phosphate is seen in the Marcellus Shale which is also associated with the regional unconformity. Initial onlap of this surface most likely produced a restricted shallow water environment which accounts in part for the phosphate concentration. This may also account for the higher concentrations of calcium in the Rhinestreet Shale in the western portion of the study area. The distribution of calcium in the Huron Shale, however, corresponds more to what has been interpreted to be the deeper water part of the depositional basin. The White Slate also shows an affinity for higher concentrations of calcium which also may be related to deeper parts of the basin. Manganese distribution in the gray shale facies is of uniformly high concentration throughout the study area. Corresponding areas of high concentration in the black shale is found in areas considered to be of deeper water.

The distribution of carbonates and sulfates is seen in Figure A31. The interpretation of this figure is rather ambiguous. For the black shale, the higher concentrations are representative of areas of restricted circulation. The high concentrations of carbonates and sulfates in the gray shale, however, are found in the deeper water portions of the basin. This is especially evident in the map of the White Slate where the concentration is low along the Warfield Anticline area which was a topographically high feature for most of the Late Devonian.

A geochemical maturity index was developed by Vogt (1927) and modified by Bjorlykke (1974) to aid in distinguishing between facies

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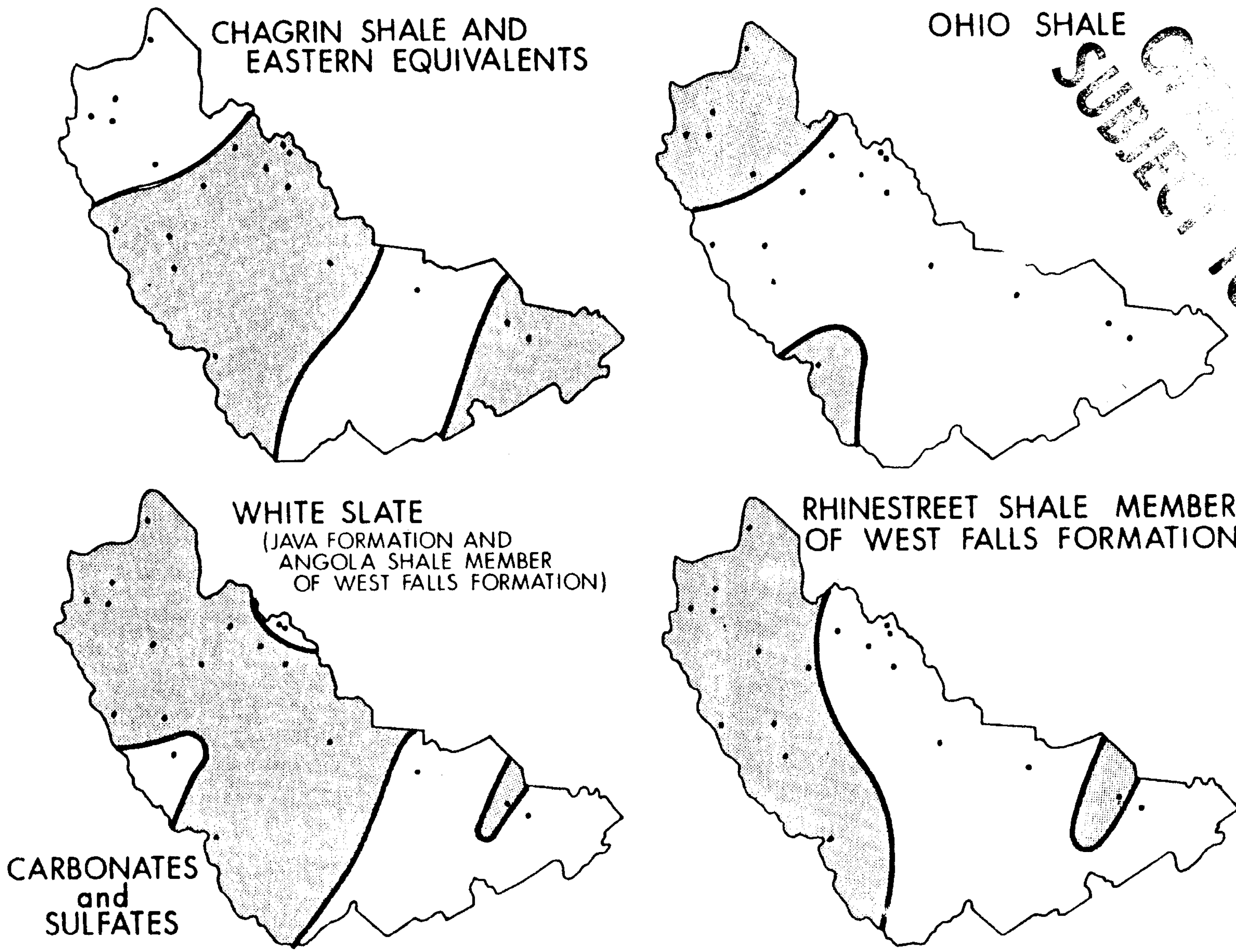

Figure A31

of different origin. The index is defined as $M=Al_2O_3 + K_2O / MgO + Na_2O$ and is controlled primarily by variations in the composition of the detrital clay minerals, especially the chlorite/illite ratio. The less mature a facies is, the lower the index will be. There is no systematic change in the maturity index values across the basin as represented in the cross section of Figure A32. This uniformity of values may represent either the overwhelming imprint of one source area or the complete mixing of sediments from multiple source areas in a restricted basin. There is likewise no systematic variation in the distribution of index values between black shale and non-black shale as indicated in Figure A33. The greater maturity of the Rhinestreet Shale sediments may indicate the great compliment of sediment incorporated from the rapidly transgressed erosional surface to the west. The most evident trend can be seen in the vertical variation of the index as illustrated in Figure A34. The general trend is for the sediments to increase in maturity up section. This may simply indicate an increase in distance from the eastern source to the deposite or a combination of an increase in distance from the source and the covering of the western source of muddy sediments.

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WEST	1	2	3	4	5	6	7	8	9	EAST
		9.0	8.6			8.4	7.7	7.8	8.5	A
	8.5	8.7	8.7	8.3	8.0	8.5	8.2	8.3	8.8	B
	7.8	8.1	8.1	8.0	8.4	8.4	8.5	8.0	9.0	C
			8.4		7.8	8.6	8.0	7.5	8.0	D
	7.0	8.9	9.1	8.7	7.8	9.0	8.8	8.0	9.6	E
						7.8	7.6	7.9	8.3	F
						8.5	7.3	7.8		G
								8.7	7.7	H
							7.9	8.2	8.2	I
							8.3		7.1	J

MATURITY INDEX

$$\frac{Al_2O_3 + K_2O}{MgO + NaO_2}$$

Figure A32

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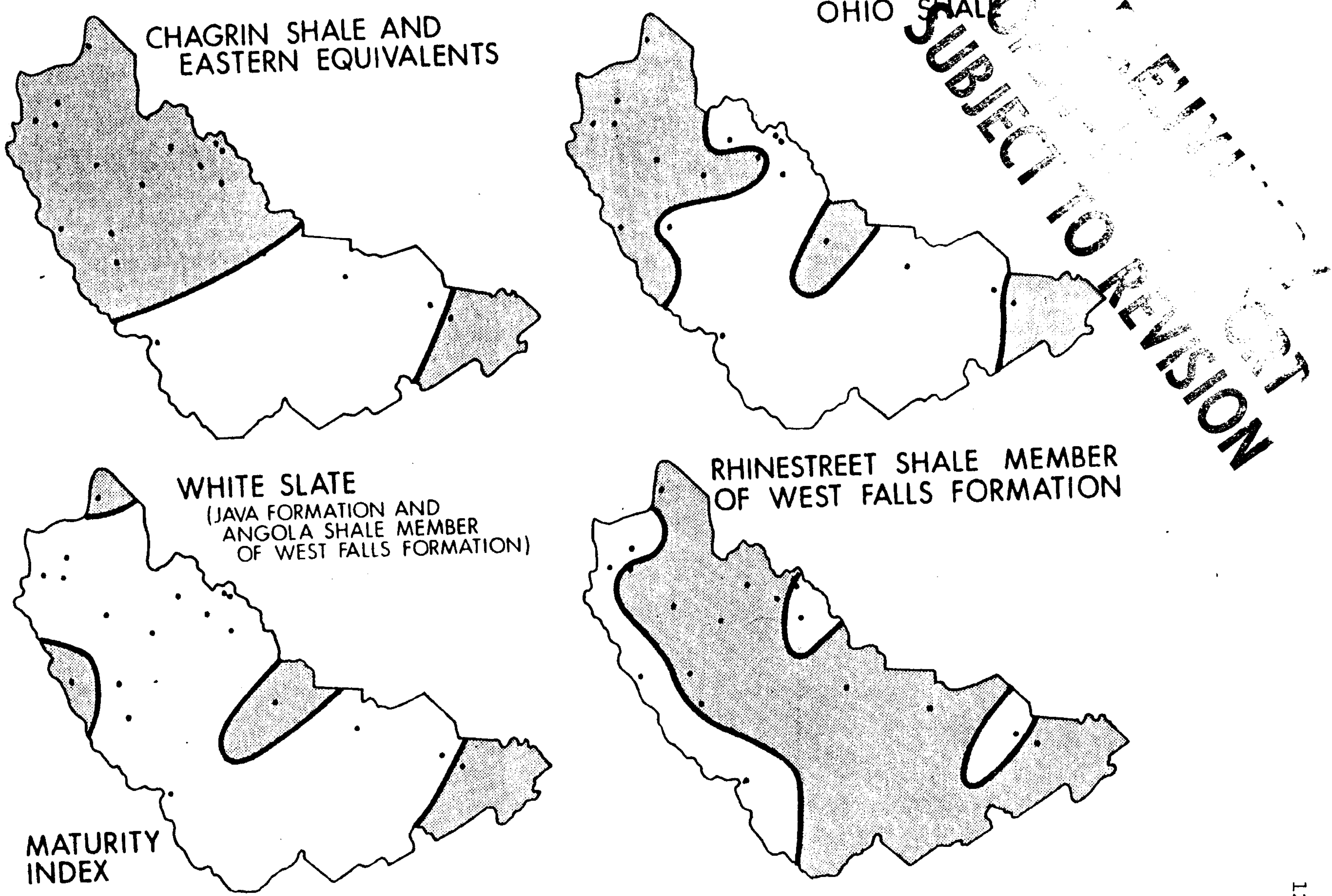

Figure A33

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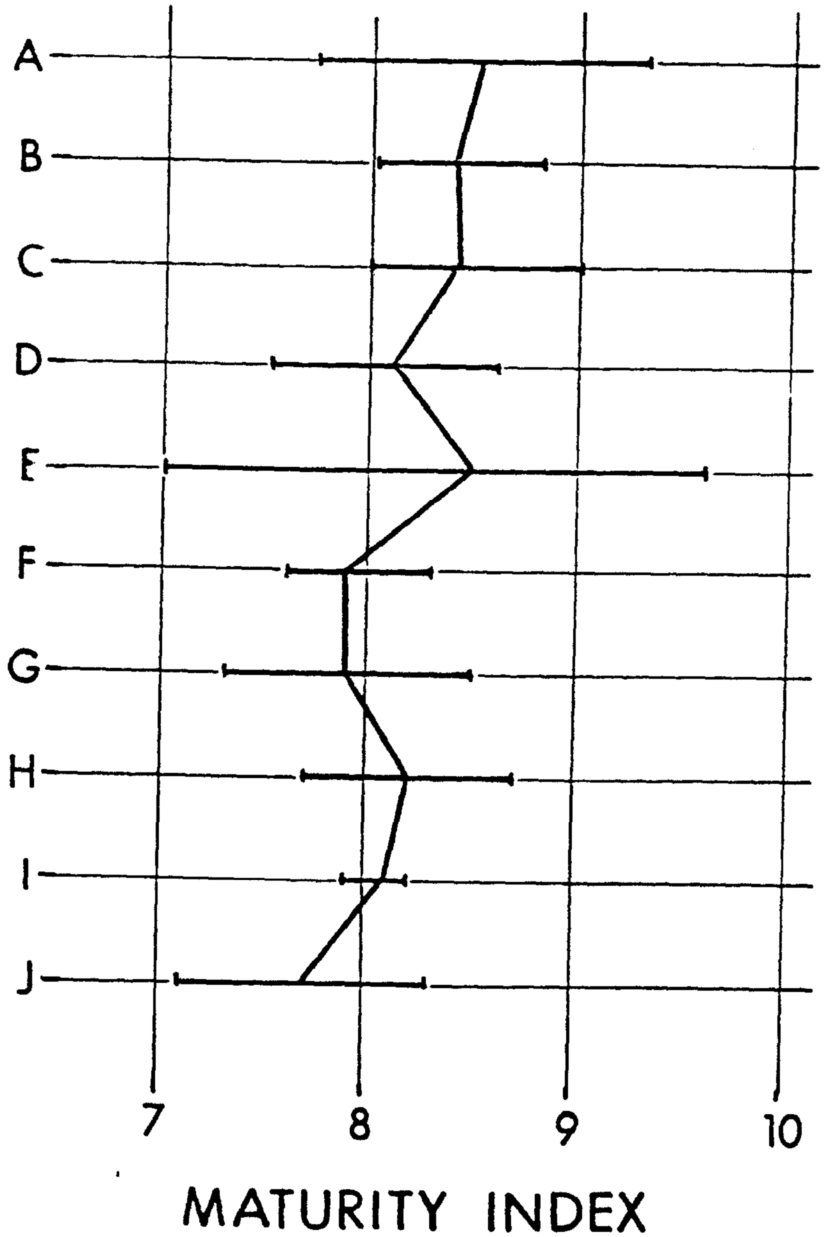

Figure A34

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APPENDIX B

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FIGURE B1
METHANE (%)
DEVONIAN SHALE GAS

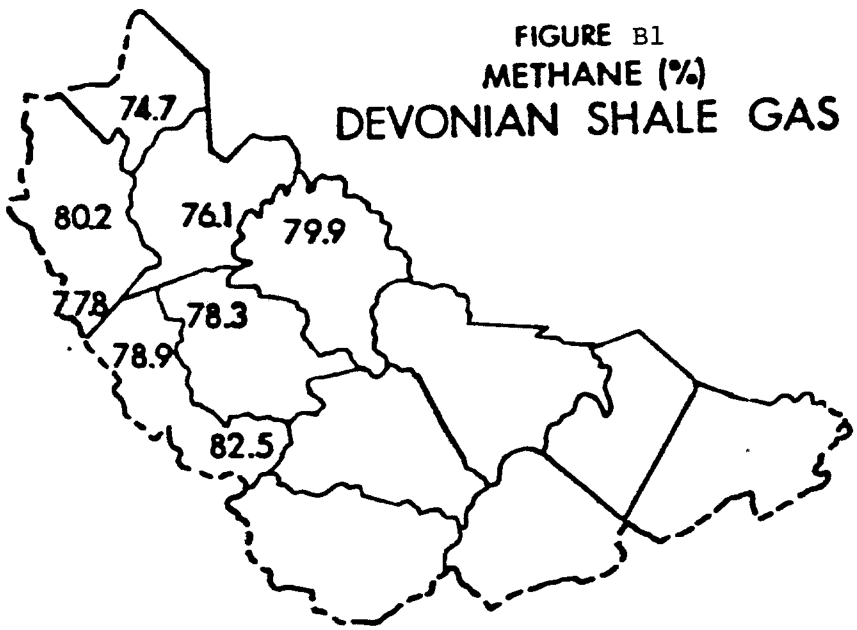
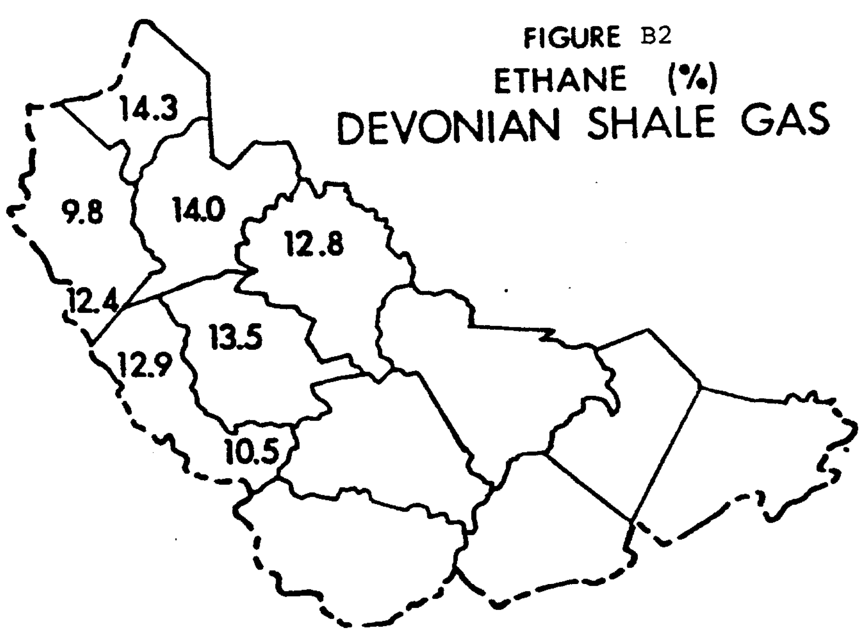


FIGURE B2
ETHANE (%)
DEVONIAN SHALE GAS



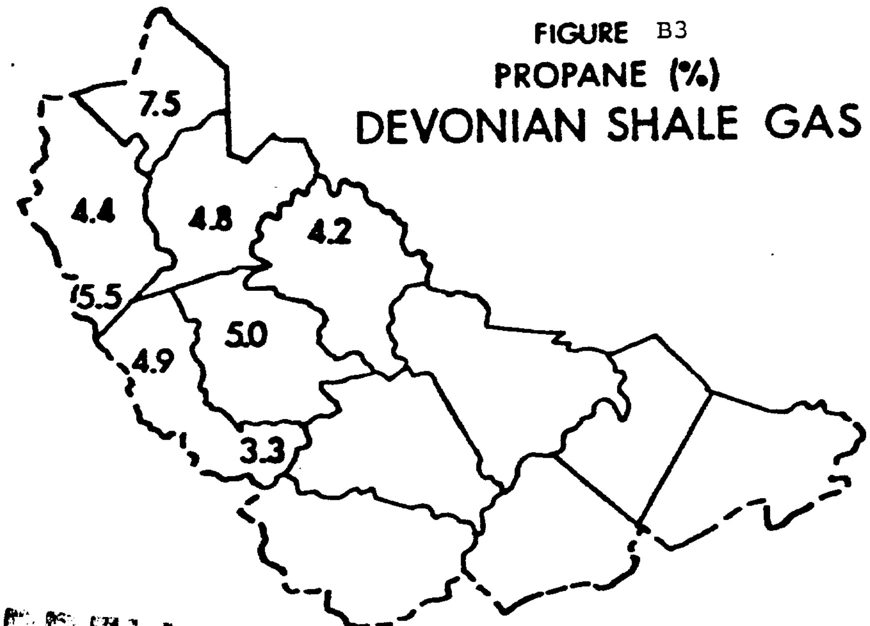


FIGURE B3
PROPANE (%)
DEVONIAN SHALE GAS

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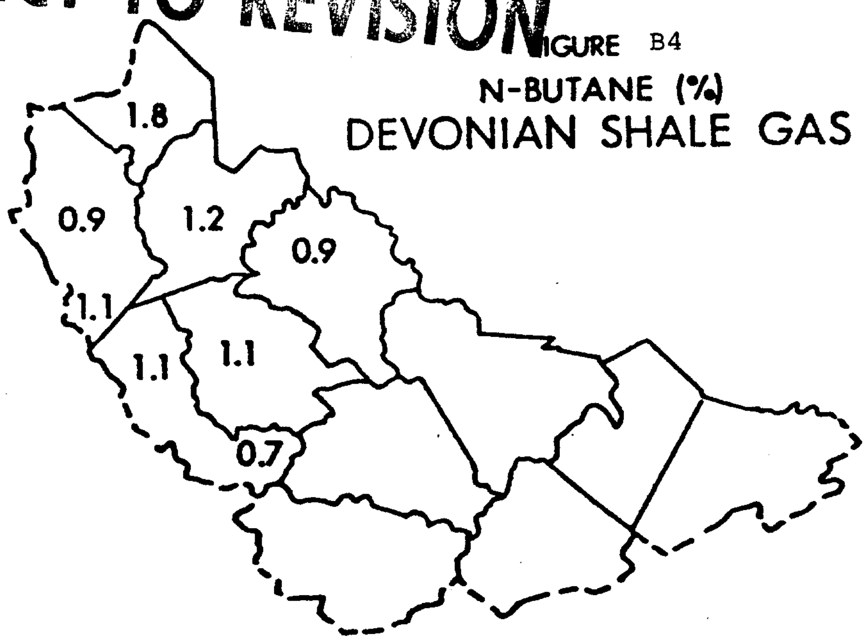

FIGURE B4
N-BUTANE (%)
DEVONIAN SHALE GAS

FIGURE B5

ISOBUTANE (%)

DEVONIAN SHALE GAS

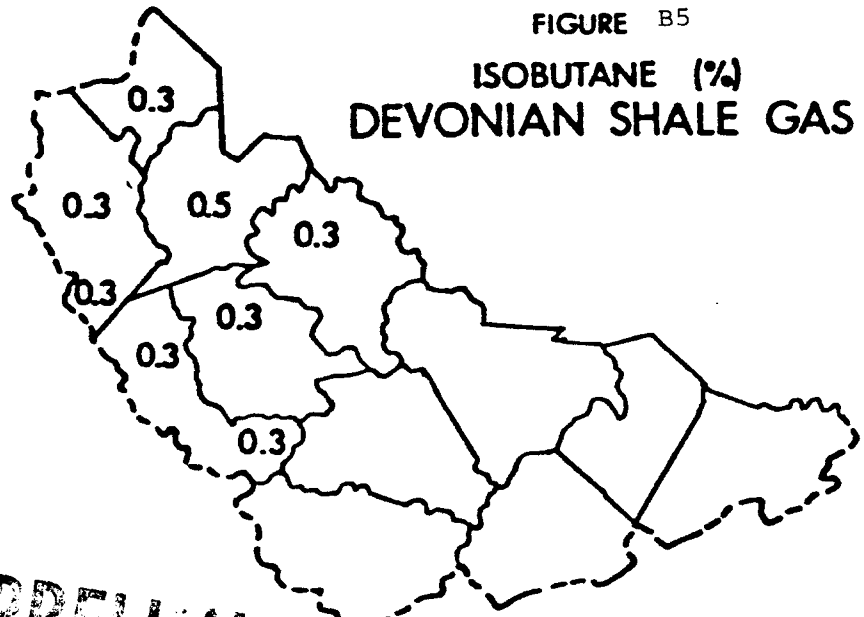

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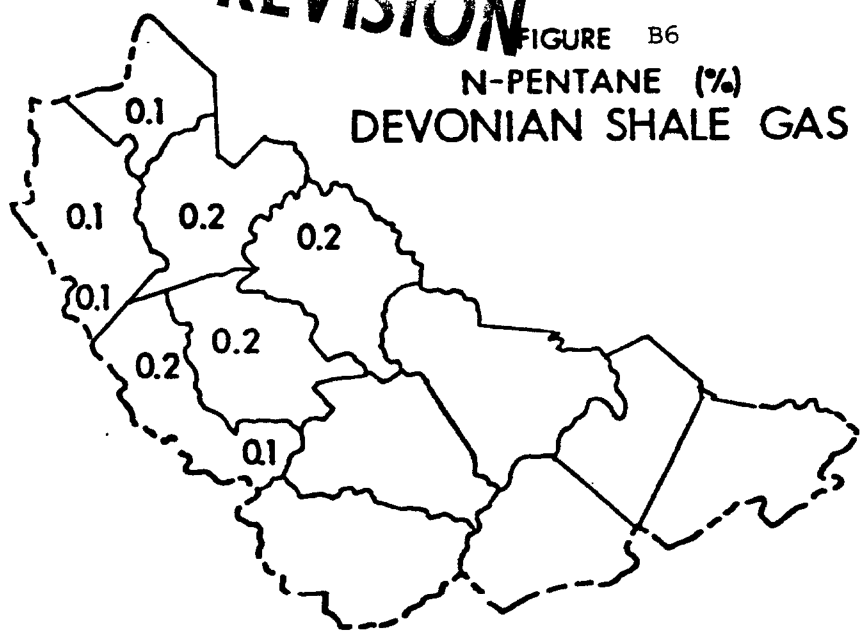
FIGURE B6

N-PENTANE (%)

DEVONIAN SHALE GAS



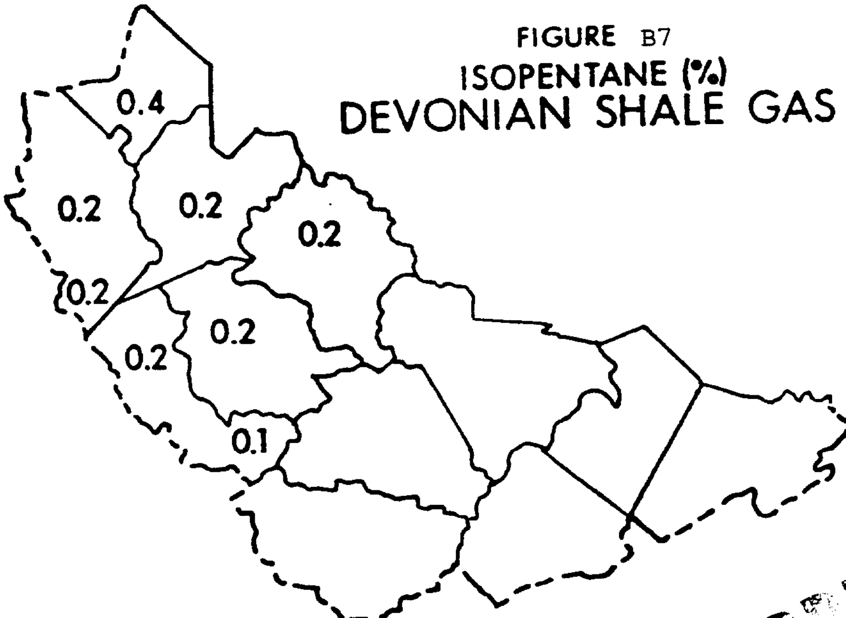


FIGURE B7
ISOPENTANE (%)
DEVONIAN SHALE GAS

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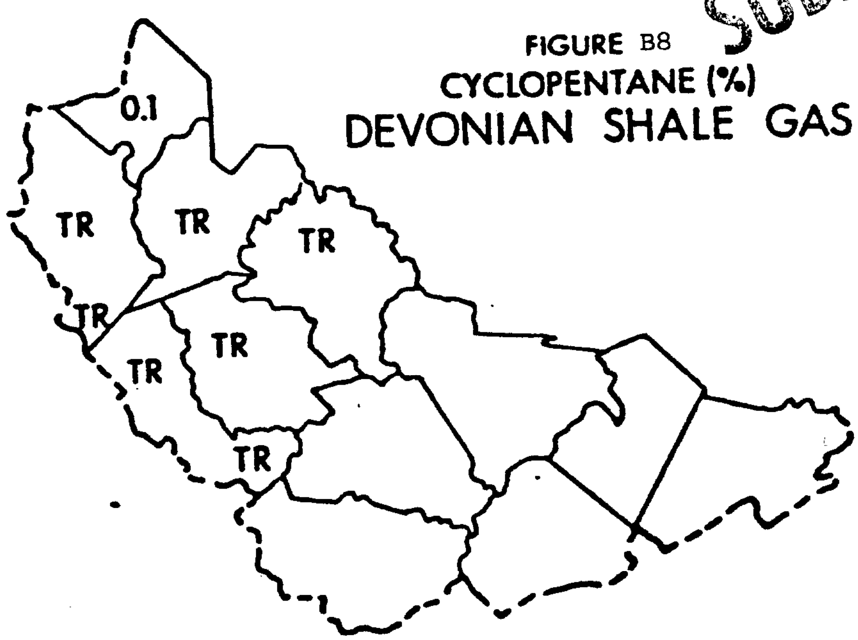

FIGURE B8
CYCLOPENTANE (%)
DEVONIAN SHALE GAS

FIGURE B9
HEXANES + (%)
DEVONIAN SHALE GAS

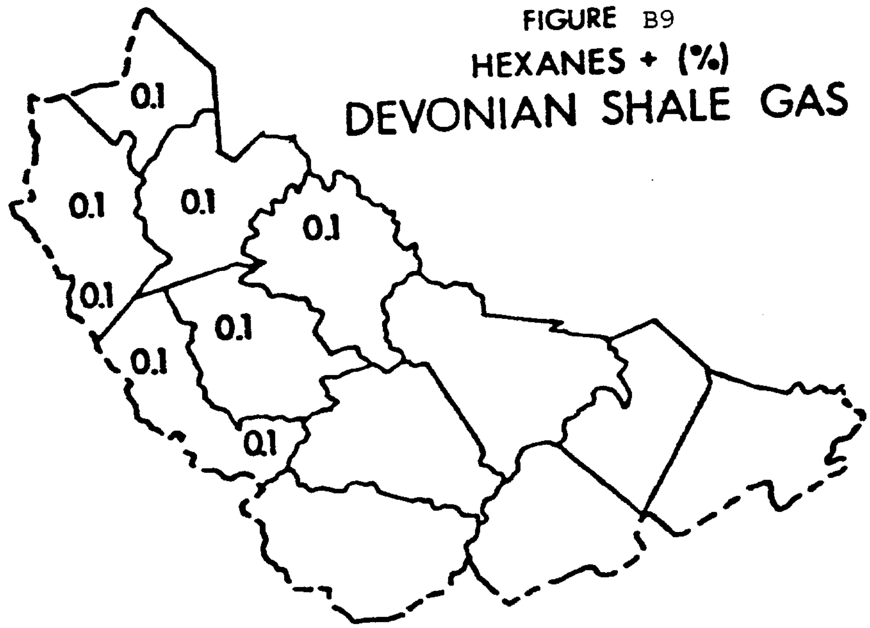

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FIGURE B10
HYDROGEN (%)
DEVONIAN SHALE GAS

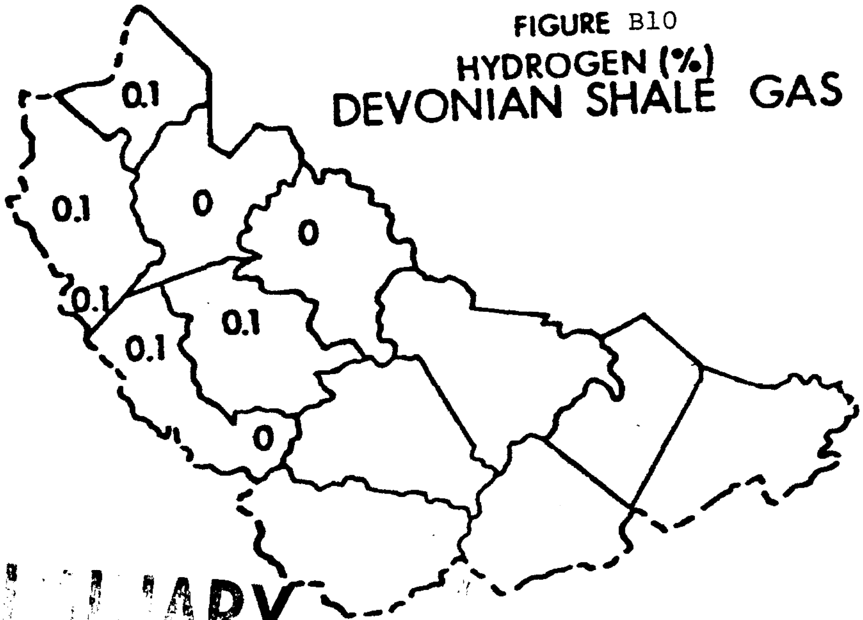

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FIGURE B11
HELIUM (%)
DEVONIAN SHALE GAS

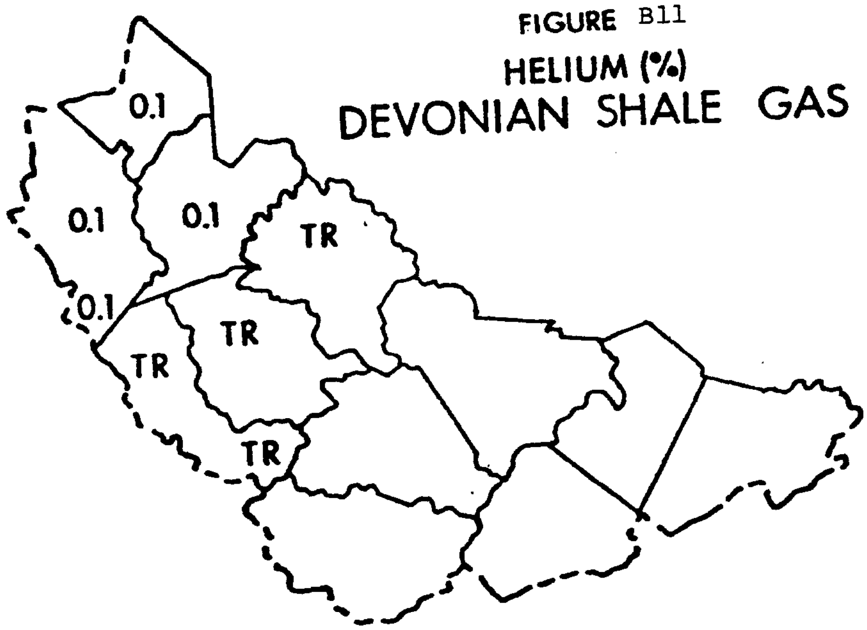

FIGURE B12
OXYGEN (%)
DEVONIAN SHALE GAS

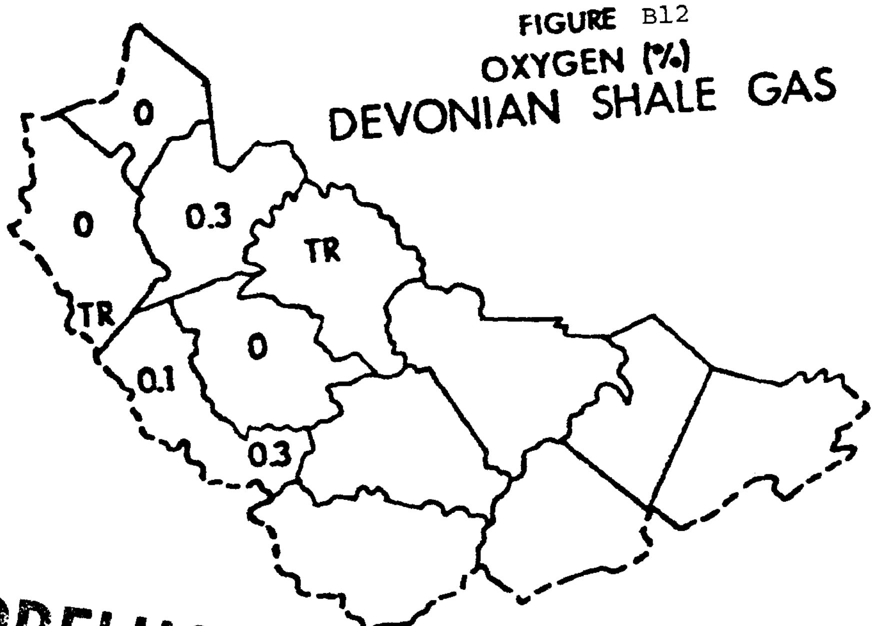

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FIGURE B13
CARBON DIOXIDE (%)
DEVONIAN SHALE GAS

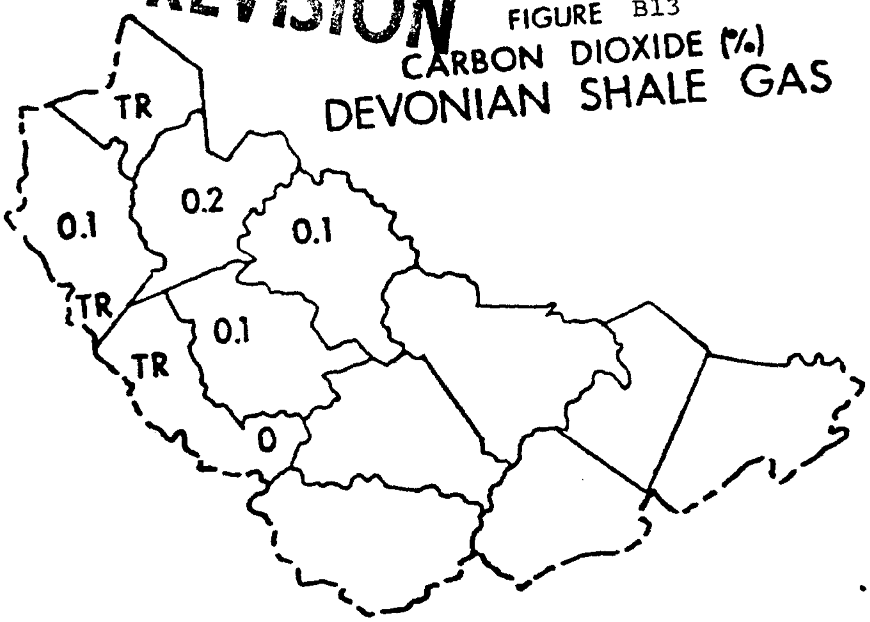

FIGURE B14
NITROGEN (%)
DEVONIAN SHALE GAS

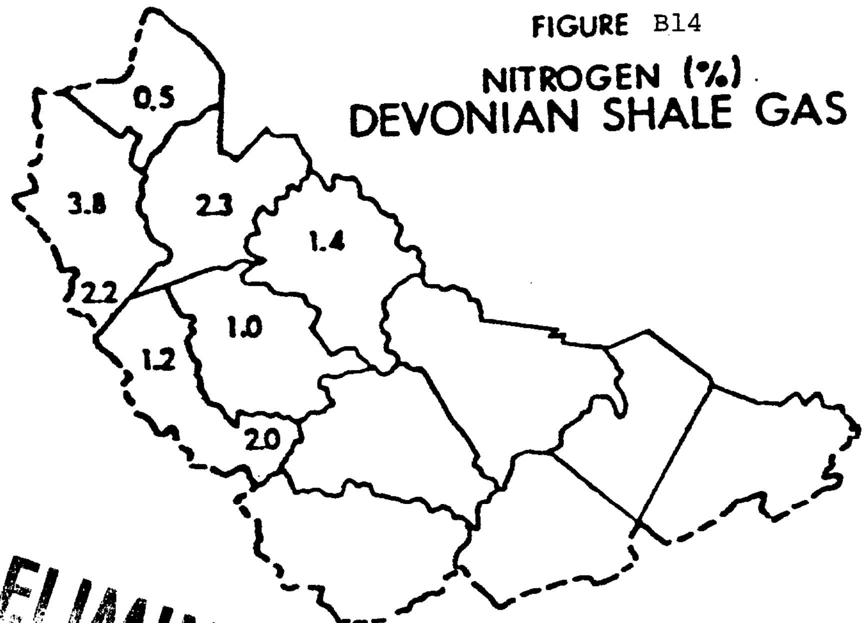

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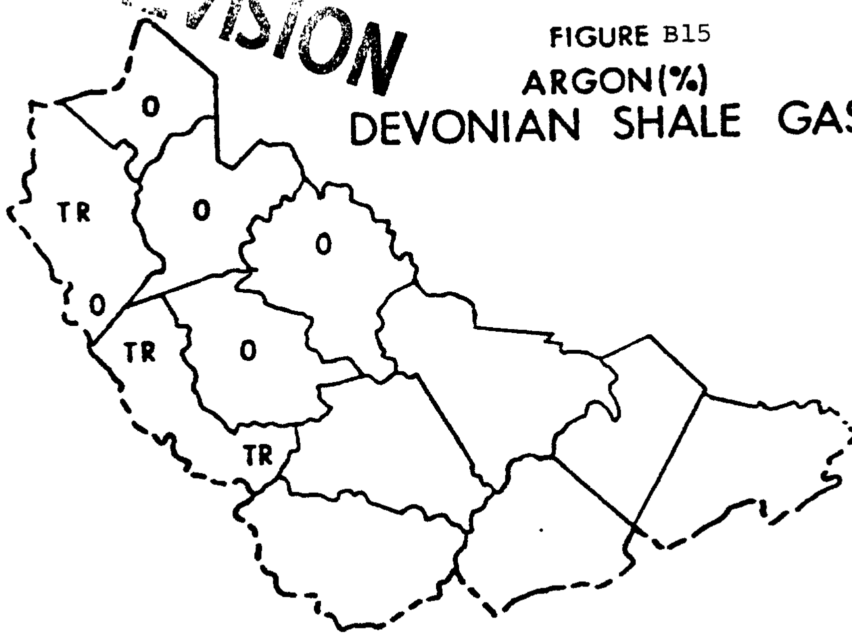
FIGURE B15
ARGON (%)
DEVONIAN SHALE GAS



APPENDIX C

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APPENDIX C

Depths to formation tops in wells used to construct cross sections and isopach maps.

Stratigraphic Units

1 Berea Sandstone
2 Bedford Shale
3 Cleveland Member of the Ohio Shale
4 Chagrin Shale and/or Undifferentiated Upper Devonian Rocks
5 Huron Member of the Ohio Shale
6 Java Formation
7 Angola Shale Member of the West Falls Formation
8 Rhinestreet Shale Member of the West Falls Formation
9 Cashaqua Shale Member of the Sonyea Formation
10 Middlesex Shale Member of the Sonyea Formation
11 West River Shale Member of the Genesee Formation
12 Geneseo Shale Member of the Genesee Formation
13 Marcellus Shale
14 Onondaga Limestone or Huntersville Chert

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Permit Number	1	2	3	4	5	6	7	8	9	10	11	12	13	14
Boone														
1021	3136	-	-	3143	4305	4909	5071	5327	5587	5627	5644	5651	5666	5686
1056	2866	-	-	2888	4266	4490	4645	4887	5103	5131	5146	-	5174	5192
1059	1960	-	-	2000	3130	3583	3729	3950	4157	4173	4188	4193	4200	4220
Cabell														
532	2175	2190	2275	2295	2560	3141	3236	3348	-	-	-	-	-	3420
534	2348	-	-	2357	2791	3377	3473	3577	-	-	-	-	-	3663
537	2025	-	-	2033	2328	3141	3240	3293	-	-	-	-	-	3332
558	2114	-	-	2123	2988	3240	3344	3490	-	-	-	-	-	3590
Lincoln														
1469	2225	-	-	2240	3380	3753	3894	4094	4280	-	-	-	4305	4330
1637	2554	-	-	2647	3407	3654	3755	3917	-	-	-	-	-	4045
1748	2132	-	-	2160	3255	3598	3737	3930	-	-	-	-	4117	4140
Logan														
864	2490	-	-	2510	3570	3957	4091	4300	4482	4497	-	-	4514	4521
McDowell														
618	3818	-	-	3834	4812	5205	5338	5542	-	-	-	-	-	5664
Mercer														
14		-	-			6230	6404	6784	7014	7592	7614	-	7720	7740
Mingo														
641	3350	-	-	3385	4493	4914	5049	5280	5390	-	-	-	-	5400
666	3262	-	-	3280	4360	4621	4752	4938	5062	5174	-	-	5182	5204
786	3716	-	-	3738	4742	5129	5279	5478	5672	5690	5697	-	5717	5730
805	2140	-	-	2180	3072	3330	3438	3618	-	[illegible]	-	-	-	3778
813	2790	2830	2892	2940	3108	4191	4333	4525						
863	2530	2553	2609	2645	2768	3580	3675	3813	-	[illegible]	-	-	-	4043
Raleigh														
289	3200	-	-	3221	4910	5318	5478	5752	6022	6353	6371	6423	6453	6473
296	3935	-	-	3940	5935	6137	6353	6679	7069	[illegible]	7805	7887	7907	7930
336	3668	-	-	3695	5365	5569	5759	6120	6408	6721	6747	6779	6811	6847
342	3263	-	-	3303	4833	5129	5322	5589	5947	6079	6103	-	6133	6165

Permit Number	1	2	3	4	5	6	7	8	9	10	11	12	13	14
Summers														
5		-	-		4805	5094	5310	5599	6005	6718	6744	6860	6890	6910
6	1905	-	-	1910	3920	4136	4395	4683	5147	6013	6051	6126	6154	6174
Wayne														
1546	1900	1930	2020	2140	2253	2742	2831	2891	-	-	-	-	-	2991
1549					2186	2573	2663	2750	-	-	-	-	-	2810
1576	1855	1880	1960	2100	2205	2620	2698	2750	-	-	-	-	-	2830
Wyoming														
688	3368	-	-	3378	4935	5157	5307	5565	5865	5995	6009	-	6037	6060

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